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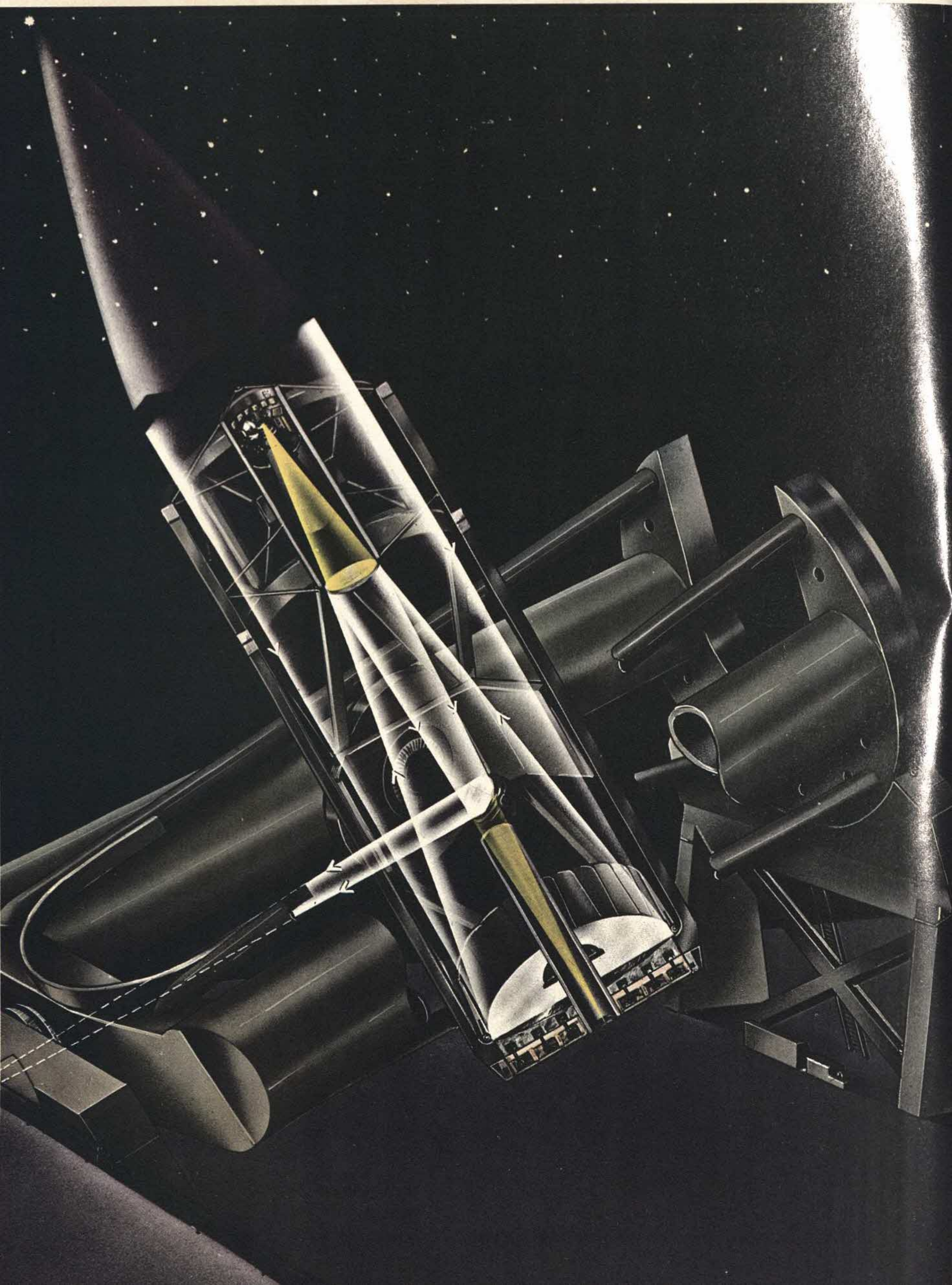
Illustrated World of Science Encyclopedia

Astronomy II:
EXPLORING
THE UNIVERSE

THE WORLD OF SCIENCE



THE WORLD OF SCIENCE

VOLUME
9
ASTRONOMY II
Exploring the Universe

with

The Illustrated Science Dictionary

CREATIVE WORLD PUBLICATIONS, INC.
CHICAGO

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VOLUME 9

ASTRONOMY II

Exploring the Universe

INTRODUCTION

In this volume the reader moves beyond the solar system to the study of stars and collections of stars. The astronomer cannot run controlled experiments on stars in his laboratory; he must observe them as they are and use his observations to uncover their nature. Once the basic nature of the stars is known, the theoretical astronomer can make detailed models of the stars and see how the models fit the observations.

One of the most basic observations is that of the spectral characteristics of the stars. These observations allow the astronomer to discover the temperatures of the stars, and the composition of their outer layers. These observations also give the astronomer information about the mass and velocity of the stars. When the spectral data are combined with a measure of the brightness of the stars in the Hertzsprung-Russell diagram, the stars can be placed in well-defined groups. This diagram provides an important clue to the evolution of the stars. As stars evolve, some of them go through a catastrophic stage and become novas or supernovas. Others may become the beautiful —if less spectacular—planetary nebulas. Observation of the collections of stars known as galactic clusters provides a valuable insight into the behavior of stars formed at the same time.

Studies of the large collections of stars known as galaxies gave rise to the concept of stellar populations. A distinction is found between old populations of evolved stars and young stars. The study of the galaxies themselves leads to a knowledge of their nature and the nature of the universe. The classification of the galaxies helps to provide an understanding of their composition and evolution. The American astronomer Edwin Powell Hubble originally classified galaxies as irregular, spiral, or elliptical on the basis of their appearance. Further studies of their stellar content and theoretical studies have led to a belief that galaxies begin as amorphous, irregular masses and evolve through spiral to elliptical forms. The study of Earth's own galaxy, the Milky Way, is in some ways easy because human beings are within it; in another sense, however, study of the Milky Way is extremely difficult because human observers cannot get an overall view. Only with the advent of radio astronomy in the past few decades has the astronomer been able to gain much knowledge of some parts of the Milky Way.

To give any kind of complete description of an external galaxy the astronomer must know how far away it is. For "nearby" objects, measuring astronomical distances involves simple triangulation, or it involves the identification of familiar objects of known intrinsic brightness in nearby galaxies. The objects used as distance indicators include well-known variable stars such as the Cepheids and RR Lyrae stars. Bright objects such as novas may also serve this purpose.

Measuring great astronomical distances to the ends of the universe involves the relationship of the observer to the universe itself. It brings to the fore the study of clusters of galaxies and the study of the structure and evolution of the observable universe. Quasars, objects most astronomers believe to be among the most distant objects that can be seen, are also among the least well understood. Present-day knowledge of these objects is comparable with the knowledge of stars some 50 years ago. The possibility that these objects may be new galaxies in formation makes their study extremely exciting.

All of these developments are discussed in articles in this volume. In addition, the tools of the astronomer continue to be studied. The tower telescope and the coronagraph are instruments specifically designed for the study of the sun. Less specialized instruments discussed are the reflecting telescope and the wide-field Schmidt telescope. Separate articles describe the appearance of the planets through the telescope and the constellations of stars. Charts of the sky for each month identify stars that can be seen with the telescope and the naked eye.

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PLANETARY NEBULAS | stars surrounded by halos of gas

A few celestial objects such as the sun and moon are well known by name; some people can identify certain of the planets and a few of the brightest stars, and thousands of others are easily visible. However, many objects in the sky cannot be seen with the naked eye, and among these are the various kinds of nebulas.

The two main categories of nebulas are the so-called extragalactic nebulas, which are actually not nebulas at all, but galaxies beyond the Earth's own galaxy, the Milky Way; and the nebulas within the Milky Way itself. Some of these are clouds (*nebula* is Latin for "cloud") of minute dust particles that reflect starlight and are, therefore, visible through telescopes. Others are sufficiently dense to obscure stars, and are called dark nebulas. Many nebulas have a relatively larger content of gas than of dust particles, and these gases are excited—in a manner to be described later—until they become luminous. All these nebulas (except for one type) are not only very distant, more than 1,000 light-years away, but they are also very large—hundreds and even thousands of light-years across —and probably are either involved in the formation of stars or represent a stage in the disintegration of stars. Such nebulas are sometimes designated diffuse nebulas, and have no special shape or apparent structure. One group of nebulas, however, is distinguished from these: the planetary nebulas. They were given this misleading name because, when first viewed in late eighteenth- and early nineteenth-century telescopes, they had the appearance of distant planets. Planetary nebulas, like many other diffuse nebulas, are essentially masses of gas; they differ from other nebulas because they do have a simple apparent shape—although they do not all have the same shape by any means and they are considerably smaller in dimension.

CHARACTERISTICS OF PLANETARY NEBULAS

A planetary nebula is essentially a gaseous mass surrounding a star of a particular kind. Its diameter, or extension across, is not easily defined, because the mass is not homogeneous; it thins out toward the edges so that it is not easy to determine just where it ends and "space" begins; but one figure suggested is a maximum of 200,000 AU (astronomical units), the equivalent of just under 3 light-years. Although this is small in comparison to the hundreds and thousands of light-years across other diffuse nebulas, it is enormous when compared to the solar system. Pluto, for example, the most distant planet from the sun, is only a few light-hours from the sun. A planetary nebula has a diameter many thousands of times greater than that of Pluto's orbit around the sun.

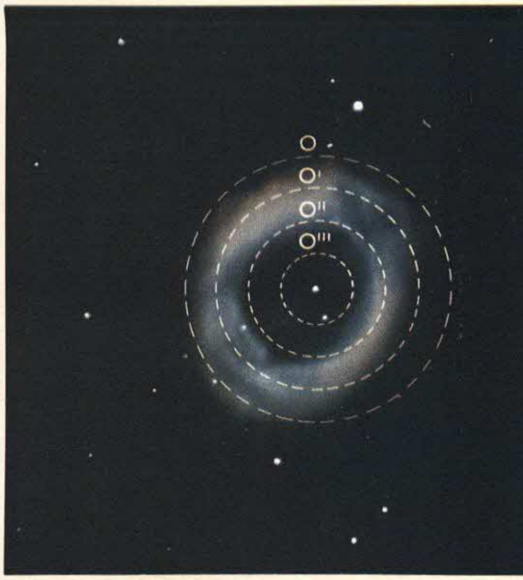
Despite this vast size, the mass of a planetary nebula is quite small—about the equivalent of the mass of a single star such as the sun. Inasmuch as this small mass is diffused over a very large space, the average planetary nebula has an extremely low density—about 10^{-18} times that of the gas composing a normal star (which in turn has a density approximately equal to that of water). The density of a nebula is about one trillionth of that of mercury. No laboratory pump on Earth could create a vacuum as rare as the gas of which a planetary nebula is composed.

Planetary nebulas seem to be ellipsoid or roughly spheroid in shape, although variations in density within them sometimes give them the appearance of shells, rings, or spirals. Their composition has not been precisely determined. When the light of a nebula is subjected to spectroscopic analysis, only those elements whose spectra are readily excited by the light of the star in the center of the nebula are easily recognizable. The principal elements identified in this way are hydrogen and helium, with lesser amounts of oxygen, carbon, and nitrogen.

INFORMATION GIVEN BY THE LIGHT

Spectroscopic analysis of the light of planetary nebulas yields other important

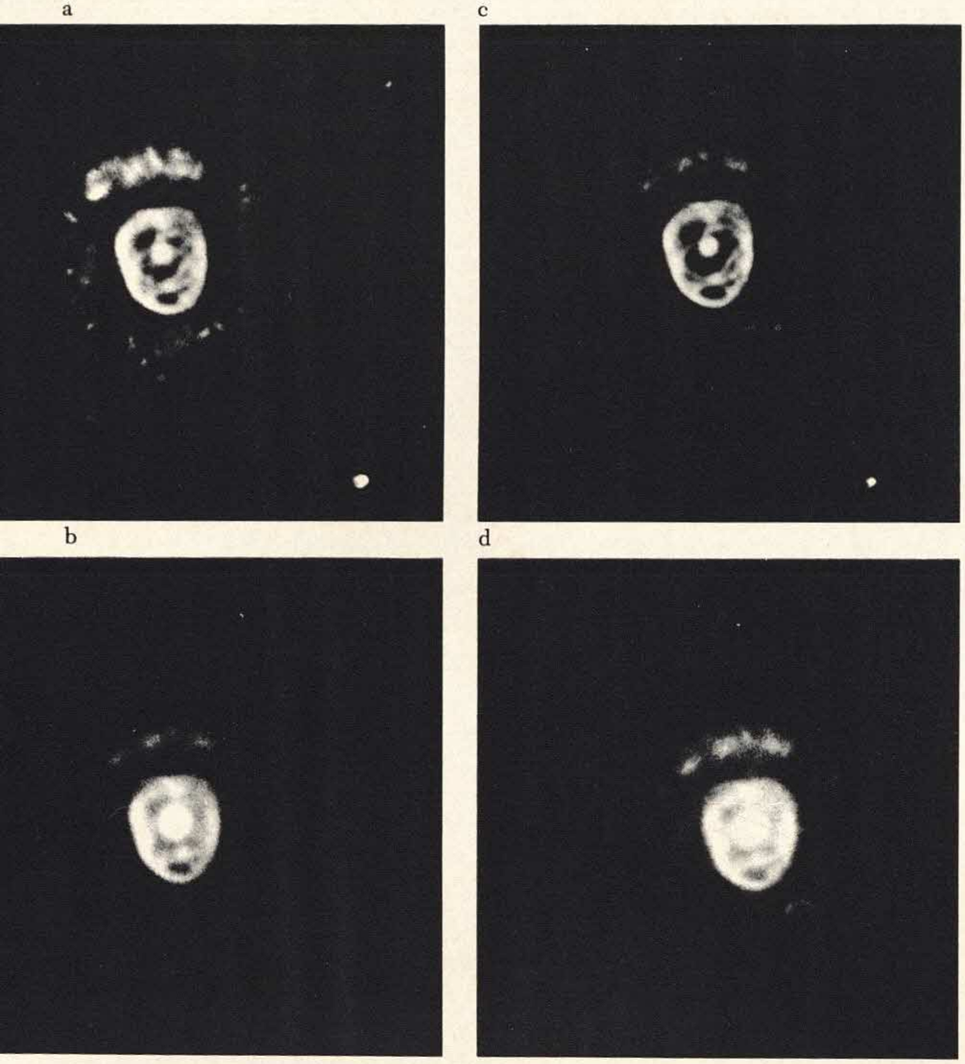
1



NEBULAR FLUORESCENCE—The light from planetary nebulas originates in the stars at their center. Each of these stars emits ultraviolet radiation, with short wavelengths approaching those of x-rays. The atoms of the nebula closest to the star absorb this radiation and re-emit it at longer wavelengths; this radiation is absorbed, in turn, by other layers of the nebula, and re-emitted at still longer wavelengths. Finally, the wavelengths are long enough to take the form of visible light.

This phenomenon is analogous to what happens in an ordinary fluorescent tube. There mercury is vaporized by an electrical discharge to produce ultraviolet radiation, which is absorbed by fluorescent material on the inner surface of the glass tube and re-emitted in the form of visible light. Studies of the spectra emitted by nebulas prove that ultraviolet radiation is absorbed and atoms are successfully de-energized to produce luminous radiation. As a matter of fact, the spectrum of triply ionized oxygen, found in the inner part of the nebula, is clearly observable; and it is possible to observe, in the outer part of the nebula, the characteristic spectrum of oxygen ions with two negative charges. It is then possible to deduce from spectroscopic analysis that singly ionized oxygen is present on the surface of the nebula, and to prove the existence of atomic oxygen in a neutral state in the outermost layer of the nebula. This means that inside the nebula are photons so energetic that they can extract three electrons from the oxygen atom—a phenomenon indicating considerable photon energy. However, as the exterior of the nebula is approached, such photons are less frequent, and the radiation is that of longer ultraviolet and visible light. The illustration shows the layers surrounding the star, and the distribution in each layer of oxygen atoms at various stages of ionization.

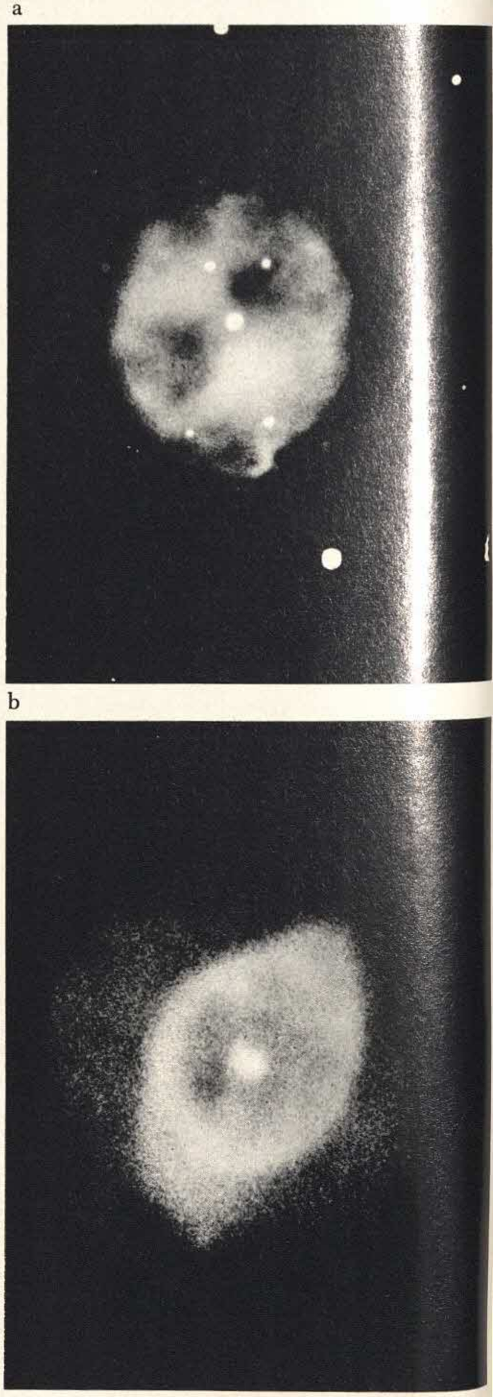
2



STUDY OF A PLANETARY NEBULA—In these four photographs, the light gathered by the telescope was filtered before reaching the film. The filter in each successive photograph allowed waves of shorter and shorter wavelengths to pass, beginning with red in the visible field (Illustration 2a), blue-green (Illustration 2b); blue (Illustration 2c); and finally ultraviolet (Illustration 2d). As the shift is made toward the shorter wavelengths, the interior part of the nebula appears more luminous. This nebula, in the constellation of Gemini, has a rather complex structure, actually that of two ellipsoidal shells.

3

STRANGE-SHAPED NEBULAS — These two nebulas have very strange shapes. The fi (Illustration 3a), composed of a double ga ous envelope, is visible in the constellati of Ursa Major, and is called the Owl Nebu because the two dark holes inside the lum ous circle vaguely resemble the eyes of ar wl. The second (Illustration 3b), compos of rather dense gas all the way to the cente ear the star, is visible only through a powerfu telescope; it is in the constellation of Hydr



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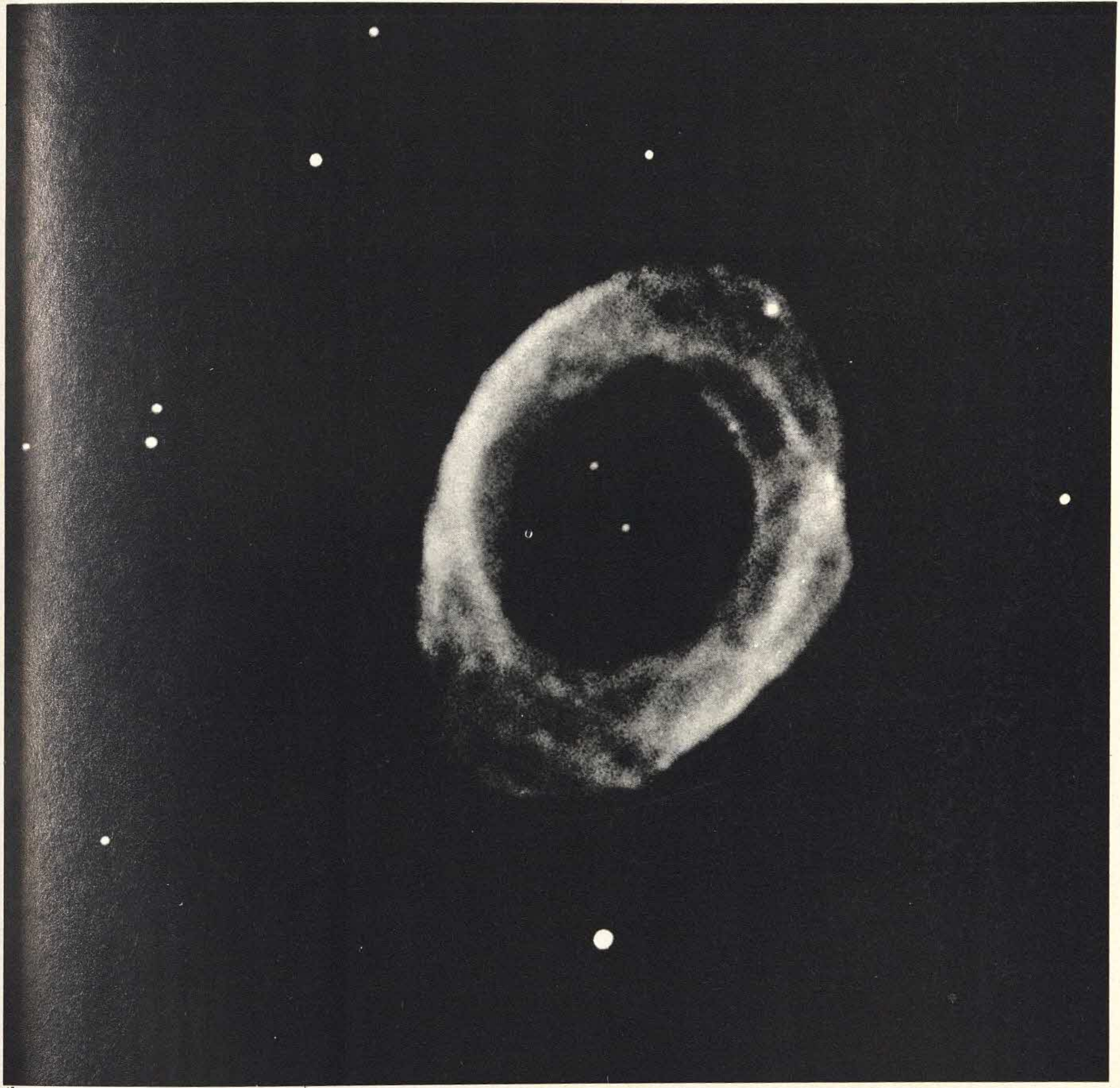
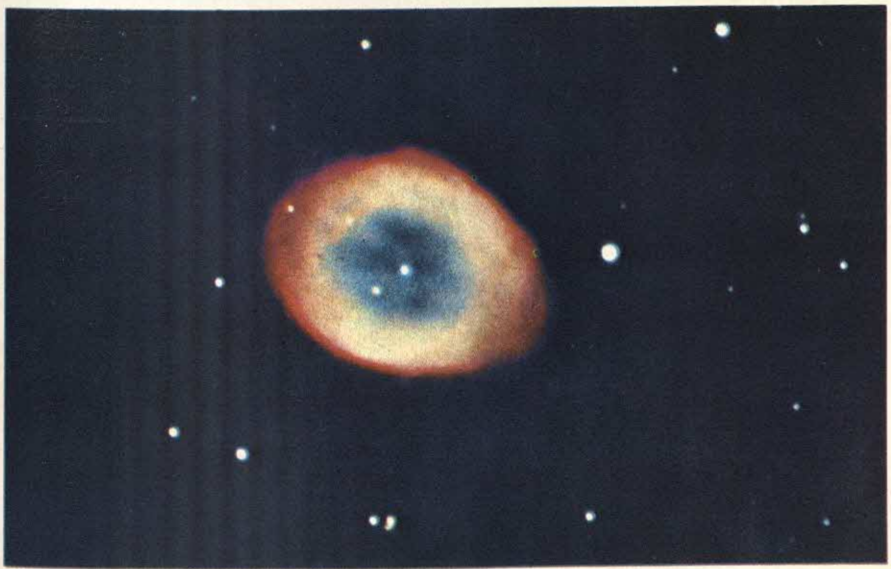
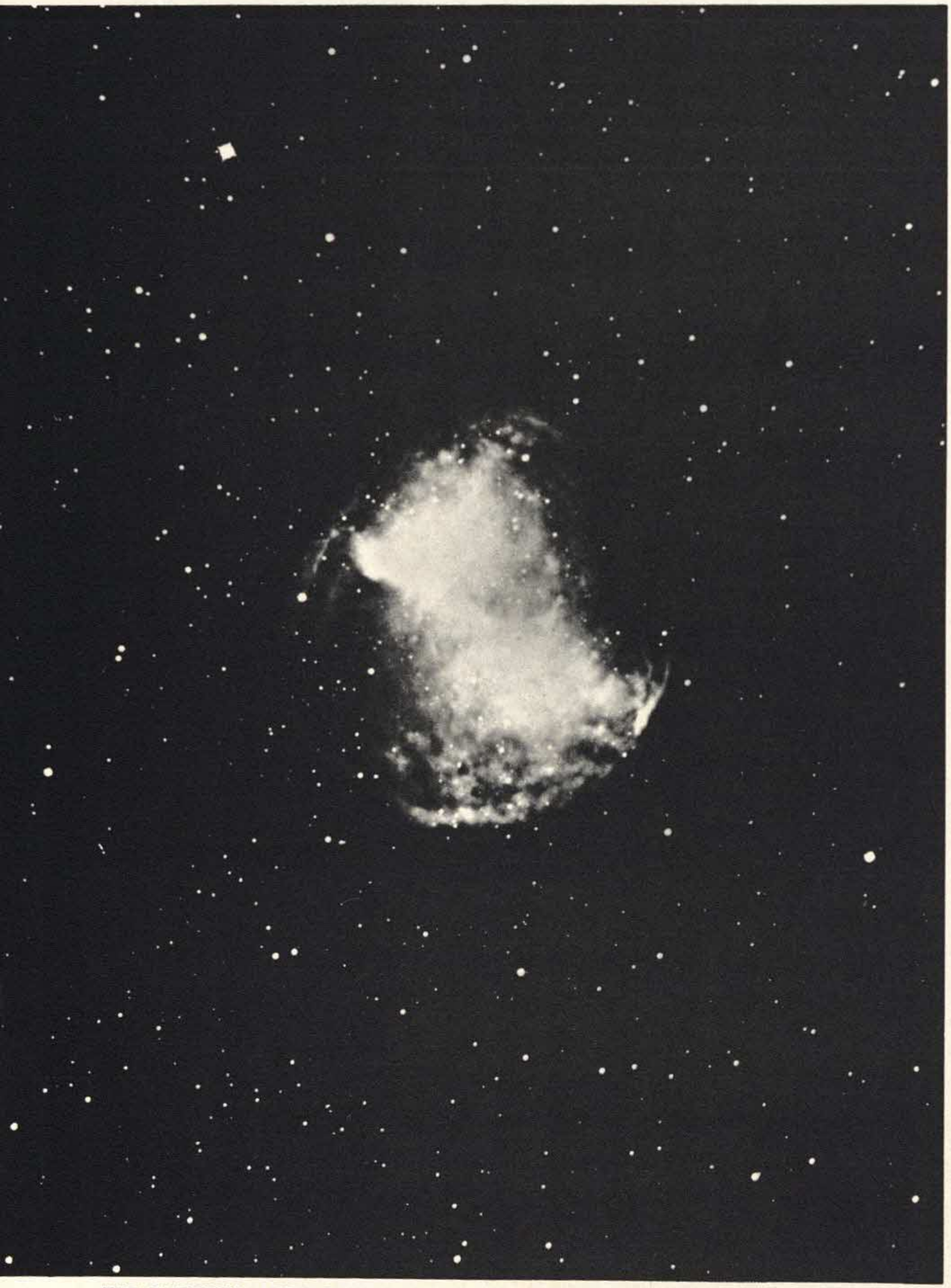


4b



THE RING NEBULA—This remarkable nebula (Illustration 4a), with its characteristic ring shape, is located in the constellation of Lyra, between the stars β and γ. The nebula can be observed with a moderately powerful telescope. Because the small star in the center emits ultraviolet radiation of great intensity, it is responsible for the luminosity of the entire nebula. This photograph, taken with the 200-in. Mount Palomar telescope, shows details of the nebular structure. As photographed in color through the same telescope, a colorful but misleading picture (Illustration 4b) results; the shading, from blue in the center to red on the outer part of the ring, indicates only a progression from the predominantly ultraviolet radiation, which registers blue on the film, to predominantly visible radiation, which registers red. When seen by eye through the telescope, the entire nebula appears bluish.

5



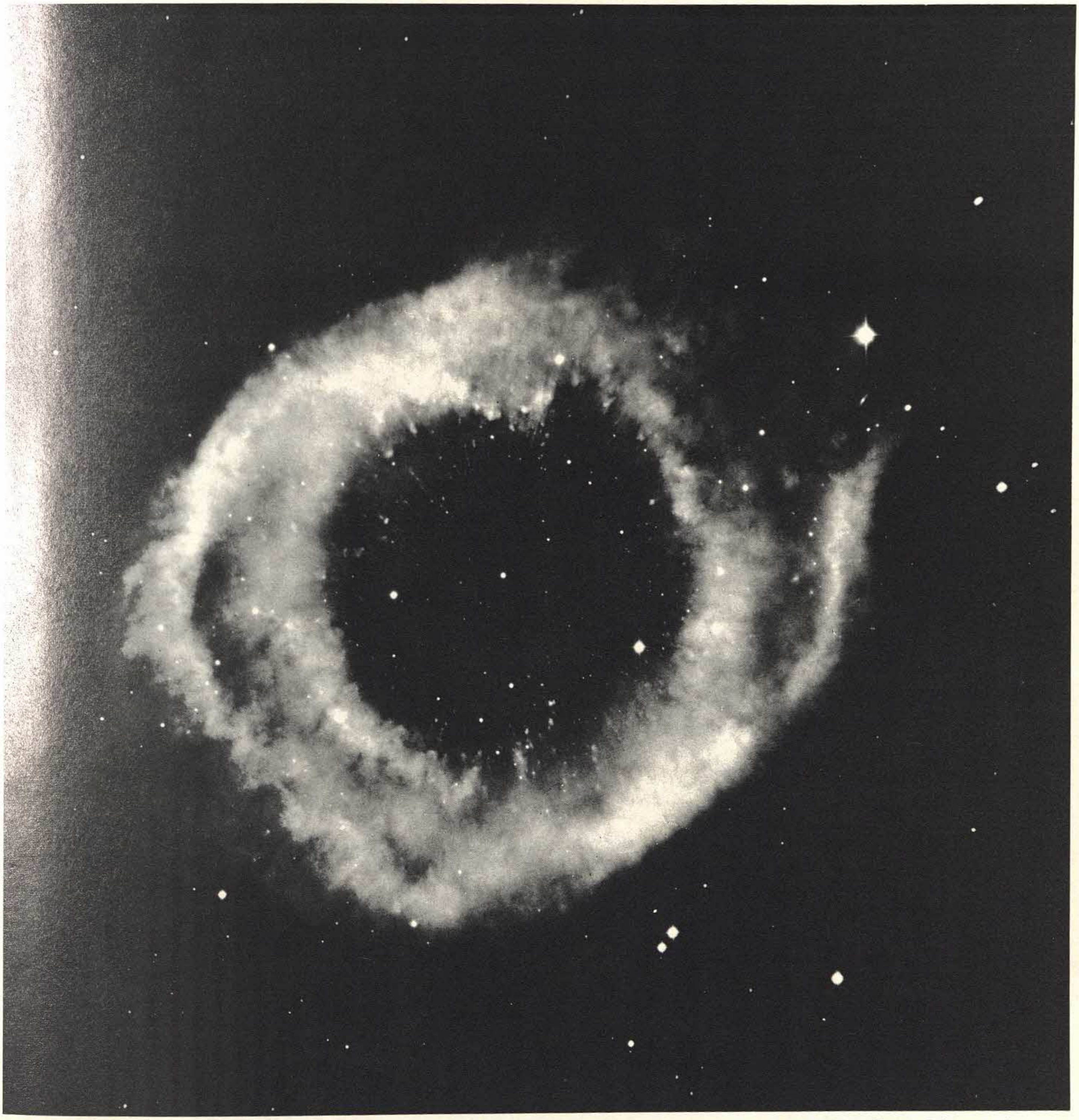
THE DUMBBELL NEBULA—If this nebula, located in the constellation Vulpecula, is photographed with a rather long exposure, it is shaped like a disk. A shorter exposure, however, reveals a dumbbell shape. It can easily be seen through a small telescope.

information—the fact, for example, that the nebulas rotate. The shift of the spectral lines over a period of time indicates that the nebula rotates on the minor axis of the ellipse in which it appears projected against the background of the sky. This rotation takes place at a limited velocity, calculated on the equator of the nebula, of about 5 to 20 km (about 3 to 12 mi) per second.

The astronomers who first observed nebulas were not always aware that each had a star at its center, because most of the stars so located emit a very weak light. However, celestial photography has made it evident not only that every planetary nebula surrounds a central star, but that these stars emit predominantly blue light. Further spectroscopic analysis showed that these stars have an extremely high surface temperature—from 50,000° to 150,000° K—and are among the hottest objects known. Inasmuch as these stars act more or less like black bodies, at these temperatures much more ultraviolet than visible radiation is emitted. This explains why the star, although visible in photographs, is almost invisible to the eye.

The ultraviolet light emitted by the star penetrates the gaseous envelope of the nebula and excites it to fluorescence, as the accompanying illustrations show. Planetary nebulas in general, although vast, are relatively not very luminous and can be distinguished only when photographed by the most powerful telescopes.

As a result, it is a certainty that the known planetary nebulas—about 1,000—are only a small fraction of those in the Earth's galaxy. Some of these are clearly visible in the telescopes of amateur astronomers, however, and afford an outstanding spectacle. Planetary nebulas serve best to draw attention to a particular process in stellar atmospheres: the ejection of material from the hottest stars.



THE GIANT NEBULA IN AQUARIUS—This is the closest of the planetary nebulas, and has an apparent diameter almost half the diameter of a full moon—some 12 minutes of arc, as compared with only a few tens of seconds of arc for other planetary nebulas. It has a ring form similar to that of the nebula in Lyra (Illustration 4). In this excellent photograph, taken with the 200-in. Mount Palomar telescope, can be seen condensations of gas from which the very intense radiation of the central star tears tails like those of comets.

SPECTRAL CLASSIFICATION OF THE STARS

sifting the stars

Less than 200 years have elapsed since a philosopher stated that it would never be possible to know the chemical composition of the stars. Only a few years after this statement, it was not only possible to identify the elements present in any star of sufficient brightness, but even to determine the physical conditions of the stars in which these same elements occur.

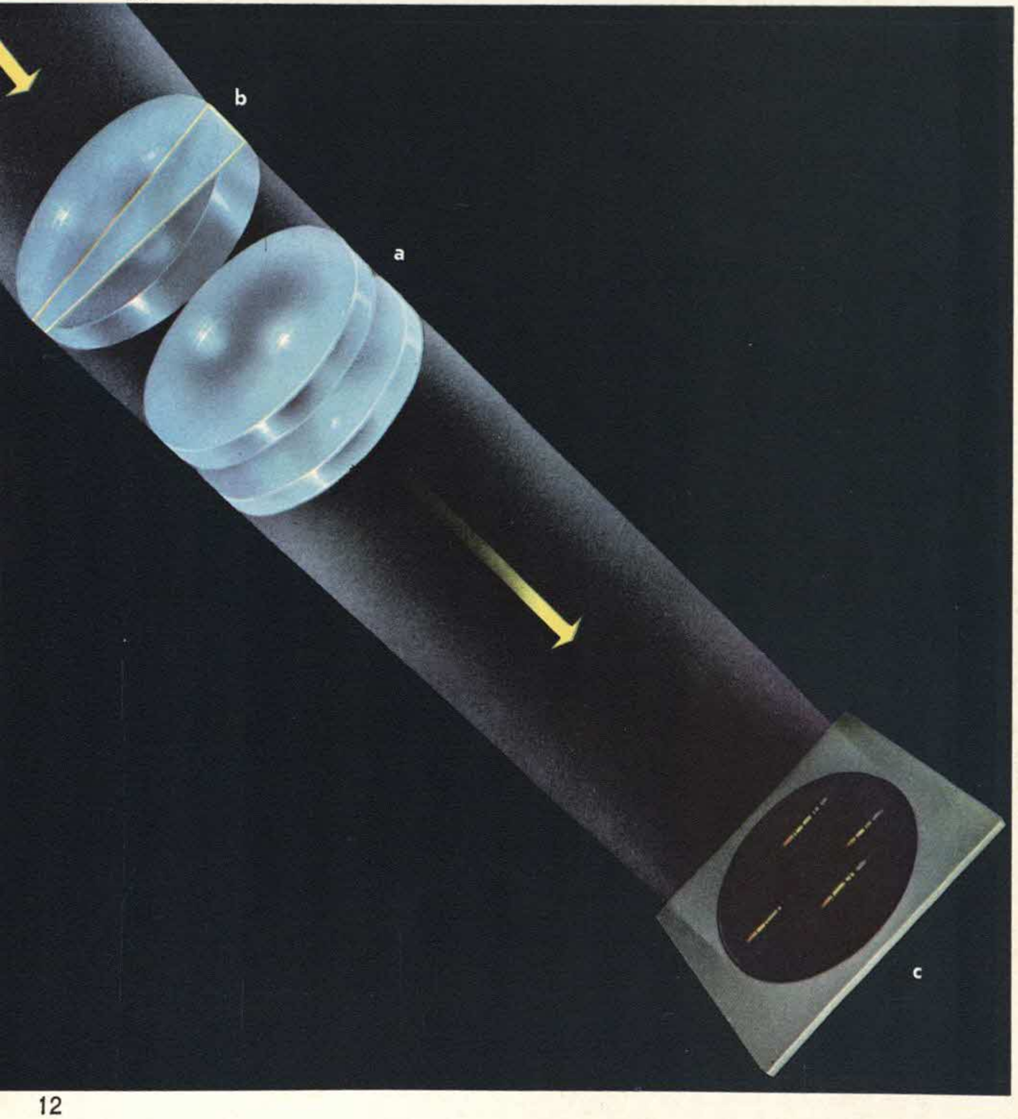
Astrophysics—the science that deals with the physical nature of the stars and the mechanism of their function and evolution—emerged in the mid-1800s. Before this, astronomers were limited to describing the visible aspects of each star—its

THE TECHNIQUE OF SPECTRAL OBSERVATION—The first observations of spectral types were carried out with a spectroscope mounted on a telescope. The spectrum was observed and the observer's decision established the spectral class. This was a very imprecise and subjective method, unsuitable for refined analysis. Later, photography replaced visual observation. Today, two techniques are used for spectral observations of stars. Illustration 1a shows how photographs are taken with an objective prism. A glass prism **b,** with a small angle at the refractory edge (5° to 7°, for example), is placed in front of the lens **a** of a large camera. The stellar images on the photographic plate **c** appear as small spectral streaks because the dispersion of light takes place in a lengthwise direction. The characteristics of the spectrum are observed with a microscope and classified. Today, analysis of stellar spectra is carried out automatically.

Illustration 1b shows a spectrograph mounted on a telescope. The light gathered by the telescope enters the slit **a,** is converted into a parallel beam by the mirror **b,** is dispersed by the diffraction grating **c,** and is focused at point **e** by an objective lens of the Schmidt type **d.**

With this instrument, only one spectrum at a time can be photographed. It has, however, the advantage that the spectrum obtained is widely dispersed and can be analyzed with great precision. A disadvantage—one, however, that is compensated for by the amount of dispersion—is the partial loss of light resulting from its passage through the instrument's prism and lens.

1a



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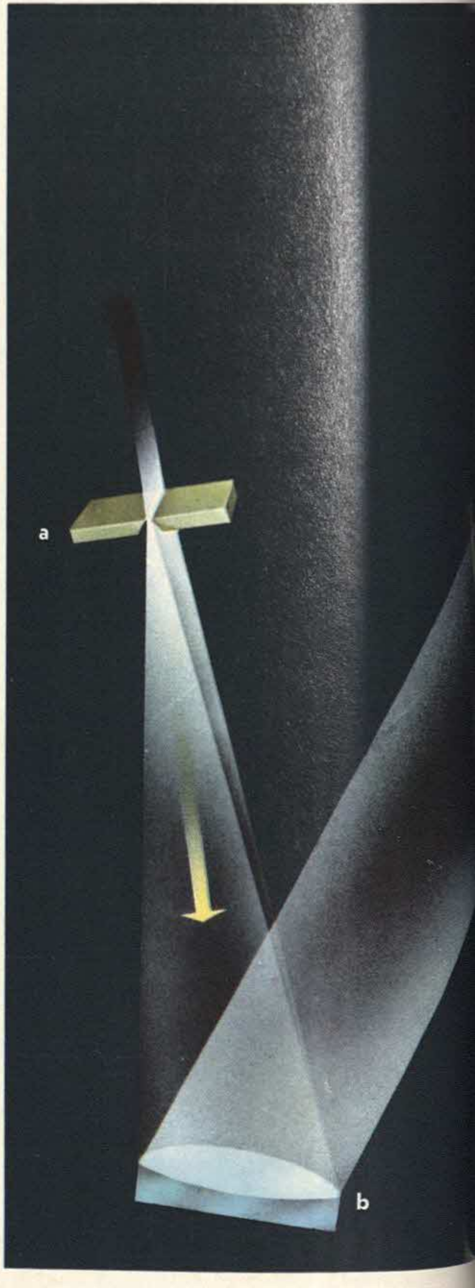
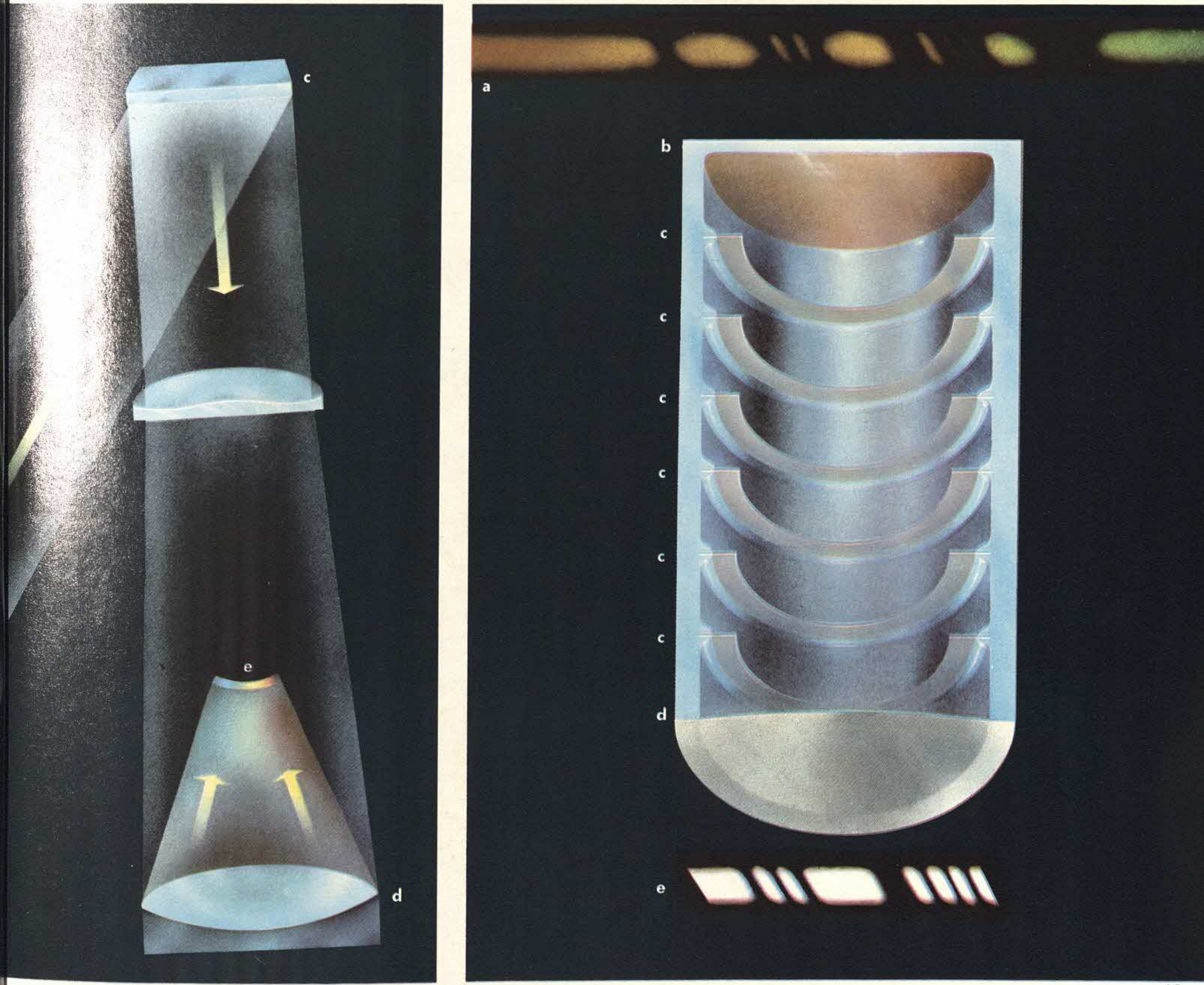


apparent luminosity, position, and perhaps the distance and motion of the star in the sky. None of these characteristics, however, were related to the star's physical nature, but only to its kinetic, static, or geometric features.

The birth of astrophysics coincided with the introduction into this science of spectroscopic analysis. This was chiefly the work of Pietro Angelo Secchi, an Italian astronomer who was the first to make a systematic analysis of the nature of stellar spectra. At first, Secchi simply classified the spectral types he observed. As a result of his pioneering work and

A modern trend in stellar spectroscopy is to add a light amplifier to the focal plane of the spectroscope in order to achieve a short exposure period for the spectrum. This allows spectra, which would otherwise require hours of exposure, to be collected in a few minutes. Illustration 1c shows a light amplifier of the type coupled to a spectrograph. The spectrum **a** is made to fall on the photocathode **b** of the light amplifier, from which electrons are extracted and accelerated by electrodes **c.** The electrons strike the fluorescent screen **d,** on which the intense image of the spectrum **e** appears. (This image is broken up to give a better idea of its increase in intensity.) The amplified spectrum is then photographed or recorded directly in code on a magnetic tape from which it is extracted and analyzed by a computer. This system has been adopted for spectroscopes mounted on space probes or unmanned satellites.

1c



subsequent progress in atomic theory and spectroscopic and observational techniques, it became possible to study the spectra of the stars in detail and from this arrive at a knowledge of their composition.

Today, astrophysics is the main branch of the science of astronomy. A wealth of information on the composition of stars has been obtained through an examination of their spectra, and this knowledge is constantly expanding.

FIRST SPECTRAL CLASSIFICATIONS

Used at first for laboratory analysis of light, the spectroscope could not be used for analysis of the extremely weak light of stars. However, two German scientists —chemist Robert Wilhelm Bunsen and physicist Gustav Robert Kirchhoff—developed a system of spectrum analysis at the University of Heidelberg in 1859, refining the spectroscope so that it could measure the light of stars observed through telescopes.

It was thought at first that the stars would differ widely in chemical composition. Astronomers expected to find as many spectra as there were stars. The systematic work of Secchi, however, clearly showed that stellar spectra were so similar that they could be classified into four groups. A fifth group was later added to make allowance for special spectral characteristics of some stars. In Secchi's classification the spectral types had these characteristics:

Type I. Spectra with particularly intense hydrogen lines.

Type II. Spectra with numerous metallic lines, although less intense than the hydrogen lines of Type I.

Type III. Spectra with bands terminating abruptly toward the red end of the spectrum.

Type IV. Spectra with bands terminating abruptly toward the violet end of the spectrum.

Type V. Spectra not included in types I, II, III, and IV.

CLASSIFICATIONS OF DRAPER AND HARVARD

Secchi's classification was perfected by the American scientist Henry Draper, who divided the spectral classes into ten basic types. An amateur astronomer, he obtained in 1872 the first stellar spectrogram and, in 1880, the first photograph of a nebula, Orion. He observed and photographed Venus during its transit of 1874. Draper analyzed the spectra of about 225,000 stars, and additions are constantly being published. Study of the resulting data revealed that stars differ mainly in the physical states of their stellar gas and only to a lesser degree in terms of composition. Moreover, the variation from one spectral class to the next is continuous and so gradual that an infinite number of intermediary stages exist. Draper's classifications are known as the Harvard sequence because of the valuable contributions made by that university's observatory to the analysis of stellar spectra.

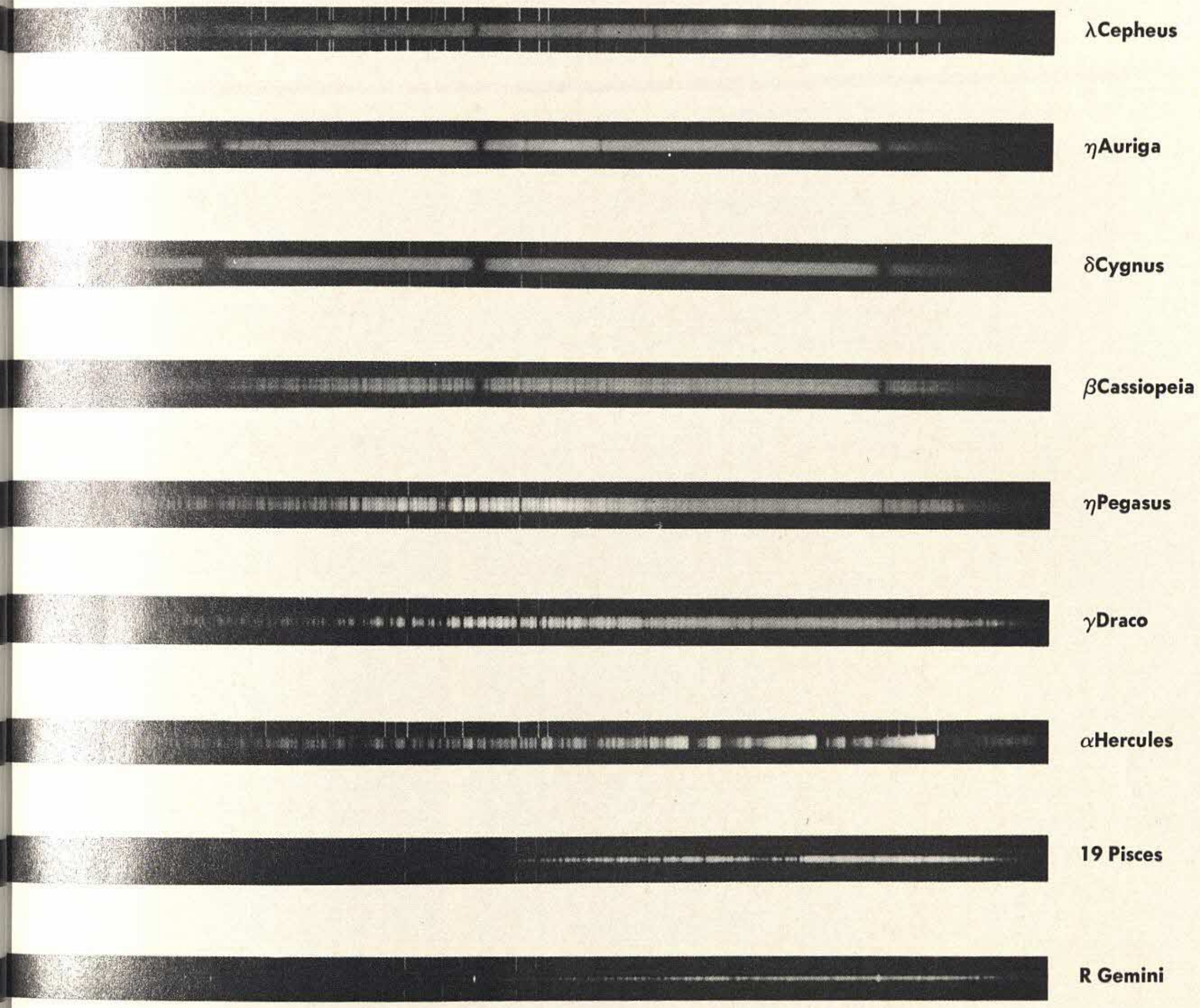
In the Harvard sequence, each spectrum is indicated by a capital letter followed by a number. The letter indicates the spectral class; the number, between 0 and 9, indicates the point at which the spectrum is to be found between the class indicated by its own letter and the following letter of the catalogue. The letters are O, B, A, F, G, K, M, R, N, and S. The spectrum G6, for instance, is slightly more than halfway between types G and K. Classes R and N have recently been combined into a new class C.

The Harvard sequence is now used throughout the world. The sequence of letters in this spectral classification corresponds to a continuous and logical variation of the spectra themselves, due to the particular characteristics of each star as reflected in its spectrum.

From class O through class M, the variation is due primarily to a decrease in star temperature. A spectrum such as R or N is known as a late class. A spectral class characterized by a magnitude number over 5, for example K8, is known as an advanced K.

2

THE MAIN TYPES OF STELLAR SPECTRA—These stellar spectra are those of very luminous stars, nearly all above the sixth magnitude. In all of the photographs, the red is on the right and the violet on the left. The extreme left approaches wavelengths below the ultraviolet limit. In the case of stars of the first spectral classes (O, B, and so forth), the limit is below 3,500 Å. For the advanced spectral classes (corresponding to stars of red-orange color), the spectrum terminates in blue or green, while emission of shorter wavelengths is very faint. In the spectra of class O stars, few lines are observed, almost all of them lines of hydrogen, helium, and a few other elements. However, these are not emitted by atoms in a normal state but by ions



and, in certain cases, ionized atoms. Therefore, analysis of class O spectra indicates that the atmosphere of these stars is subjected to extreme temperature conditions. In the spectra of class B stars, only the lines of hydrogen, neutral helium, and a few other un-ionized elements such as nitrogen, are evident. In class A spectra, on the other hand, more intense hydrogen lines are seen. This increase in intensity is due to the special conditions of the atmosphere of the star—conditions of pressure and not of temperature. It is difficult to observe the lines of helium, which disappear completely in the last few classes.

In the following spectral classes, the hydrogen lines continue to diminish in intensity. Already, in A, the spectral lines of some ionized metals can be seen. The first metals to appear are calcium, magnesium, and iron.

The next spectral class (F) is characterized by very weak hydrogen lines and a great number of metallic lines, which can be seen throughout the spectrum. In class G, to which the sun belongs, lines of many metals are evident. The hydrogen lines are clearly visible but are not so intense as the lines of ionized calcium. Lines of molecular bands appear in this spectrum. Stars having spectra at the beginning of the spectral sequence have, in fact, a high temperature. Continuing down the spectral classifications, one moves toward the colder stars (colder at least in their atmospheres)—stars in which molecules and radicals are easily formed.

In the spectra of class N and onward, molecular bands are prominent. In class M spectra, the lines of titanium oxide are intensified; in R and N, on the other hand, the bands of cyanogen and diatomic carbon are intensified. Finally, in class S, bands of zirconium oxide are clearly visible.

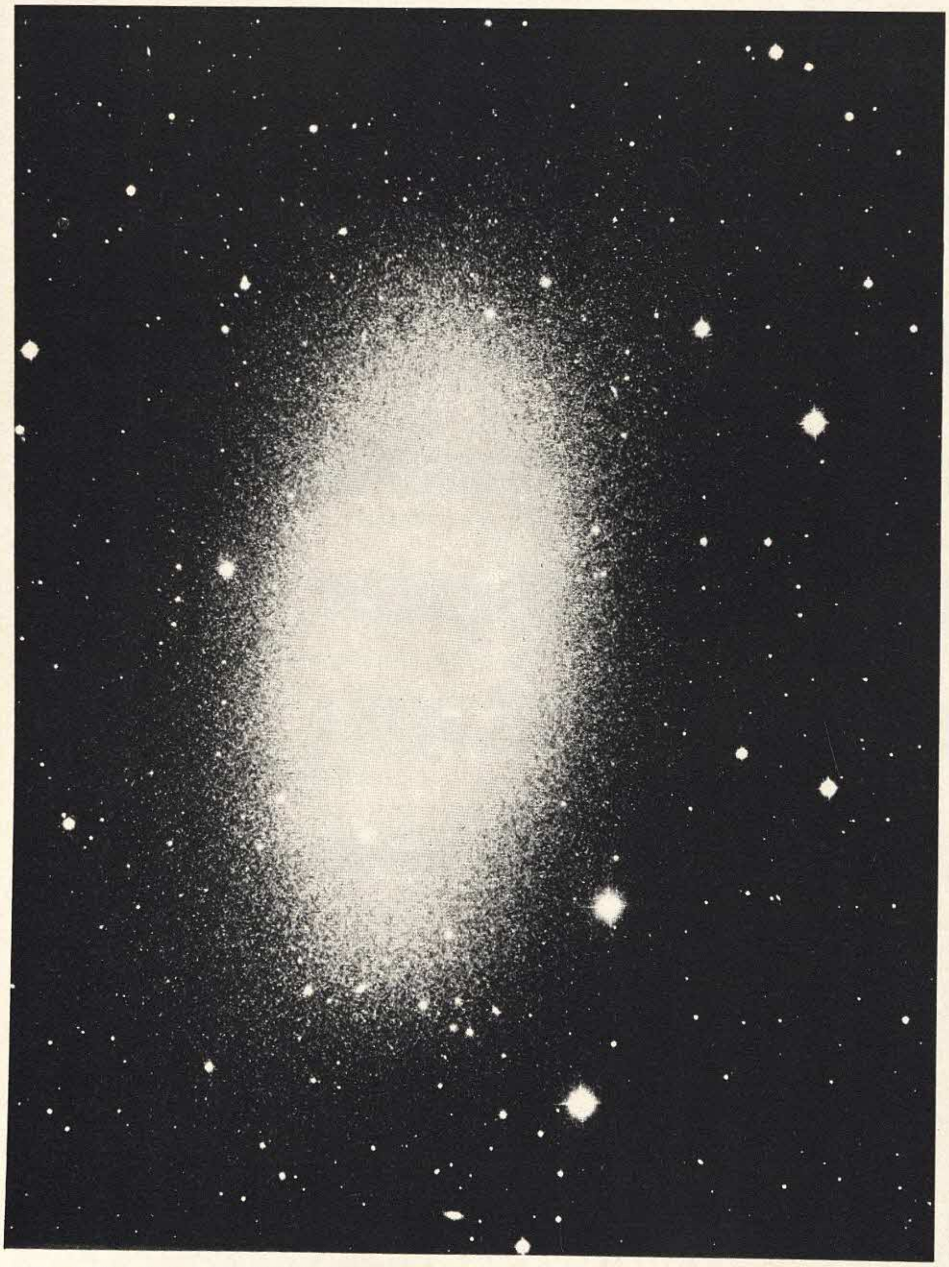
In analyzing spectral classes, seemingly unimportant differences occur in different stars within each class—for example, the intensity ratio between the various lines. These differences are used to determine the physical characteristics of the stars—their diameters, surface tensions, and temperatures.

When listed in their spectral order, the stars fall into a sequence of diameter, mass, absolute luminosity, surface temperature, and color.

STELLAR POPULATIONS | groups of stars, old and young

Analysis of the light of a star by means of a spectroscope provides numerous clues that indicate the star's physical characteristics—its diameter, its mass, and its surface temperature; its chemical composition; whether it rotates on its own axis, and if so, at what velocity; whether it is expanding or contracting; whether it has magnetic fields, and of what intensity. Observation of stars by the naked eye suggests that they might be, if not identical, at least very similar to each other. As a matter of fact, they are very different, inasmuch as their characteristics vary in many respects. The luminosity of two stars can differ as much as the brightness of a lighthouse and a firefly. Even stars that seem to

1a



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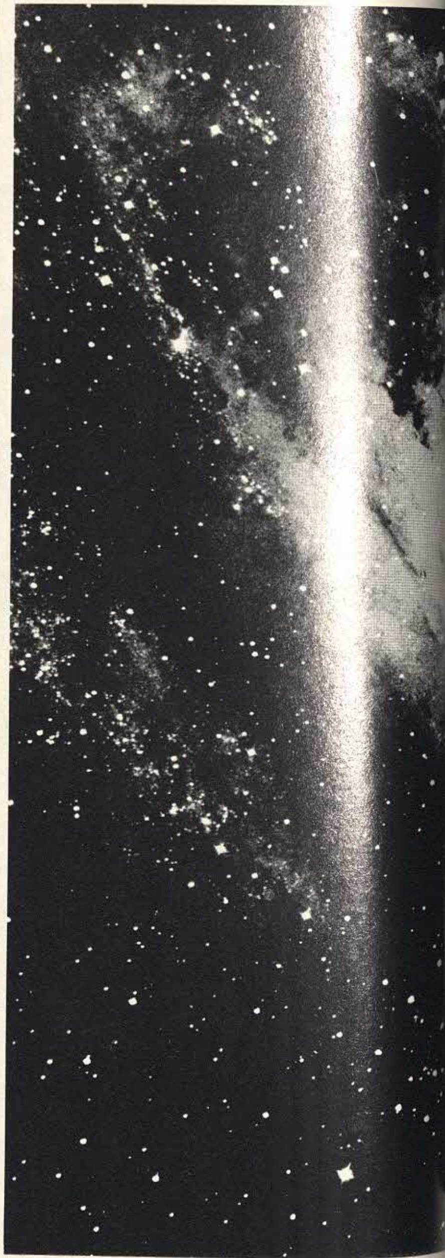
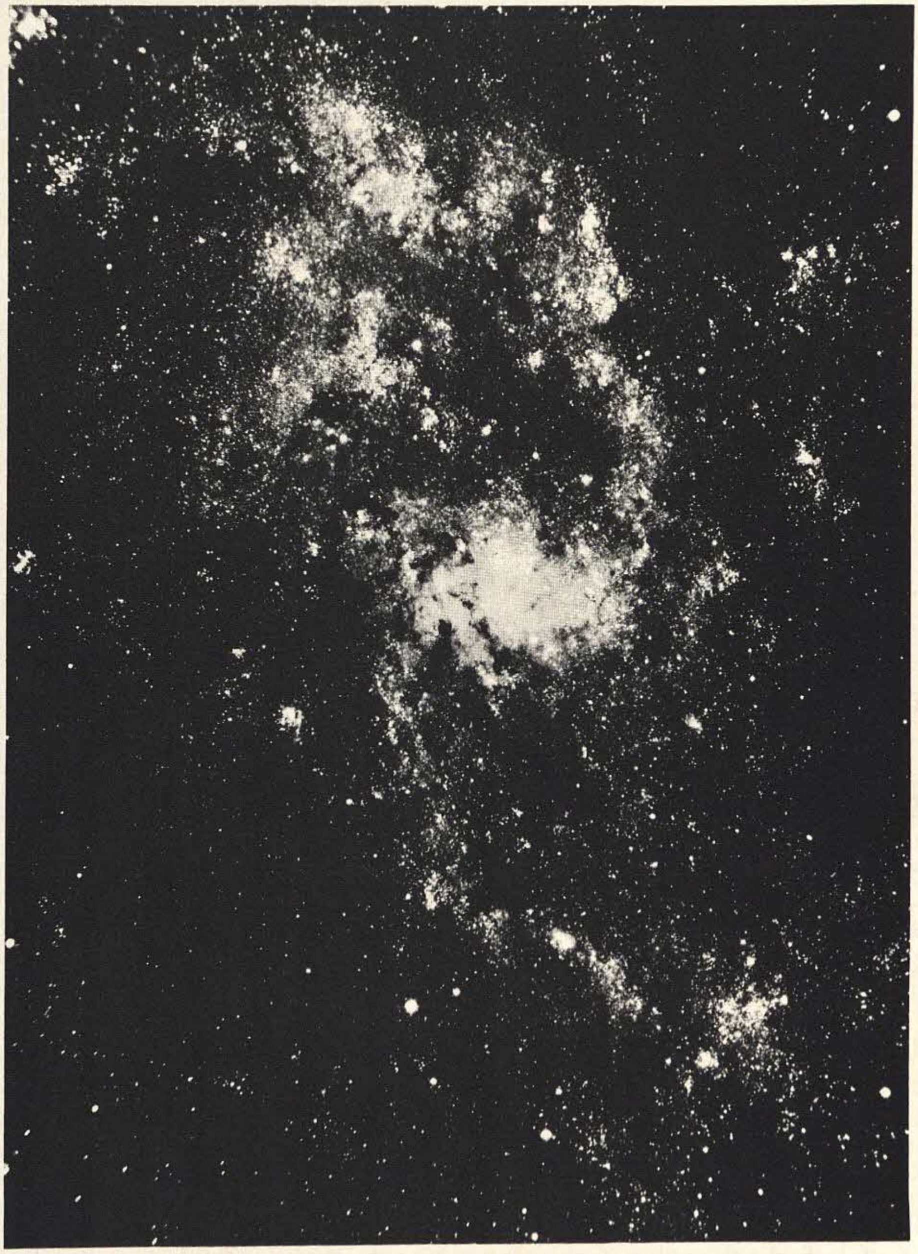


POPULATION AND EVOLUTION—These three photographs point out very clearly the difference between systems composed of different stellar populations. Galaxy NGC 205, the same galaxy that is shown in Illustration 3b, appears here (Illustration 1a) in enlarged scale, making even more obvious the relative uniformity and large number of stars in the galaxy, the absence of interstellar matter, and the regularity of the galaxy's shape. Red stars of normal size, such as those in this galaxy, are relatively old in the astronomical time scale; the system composing this galaxy is, therefore, relatively old; but enough time has passed for the stars to have moved around the center of mass of the system in such a way as to have caused variations and produced the regular shape of a galaxy of population type II stars.

The center of the Andromeda galaxy, also shown in the inset of Illustration 3, appears in enlarged scale (Illustration 1b). The central area of the galaxy, as shown in the center of this photograph, is populated by stars that cannot be distinguished separately because of their great number and poor luminosity. As seen through the 200-in. Mount Palomar telescope, this area seems to be composed of have the same characteristics are to some extent dissimilar.

However, all the stars that form the systems composing the universe tend to group according to common characteristics. For example, all the brightest stars in a globular cluster vary only slightly in luminosity. However, those in an open cluster, such as the famous cluster of the Pleiades, vary noticeably in luminosity although they all have the same bluish-white color. The color indicates the spectral class, and this in turn locates the star in the Hertzsprung-Russell diagram (which shows the relationship between luminosity and surface temperature or spectral class), and helps in classifying many of the other characteristics by

1c

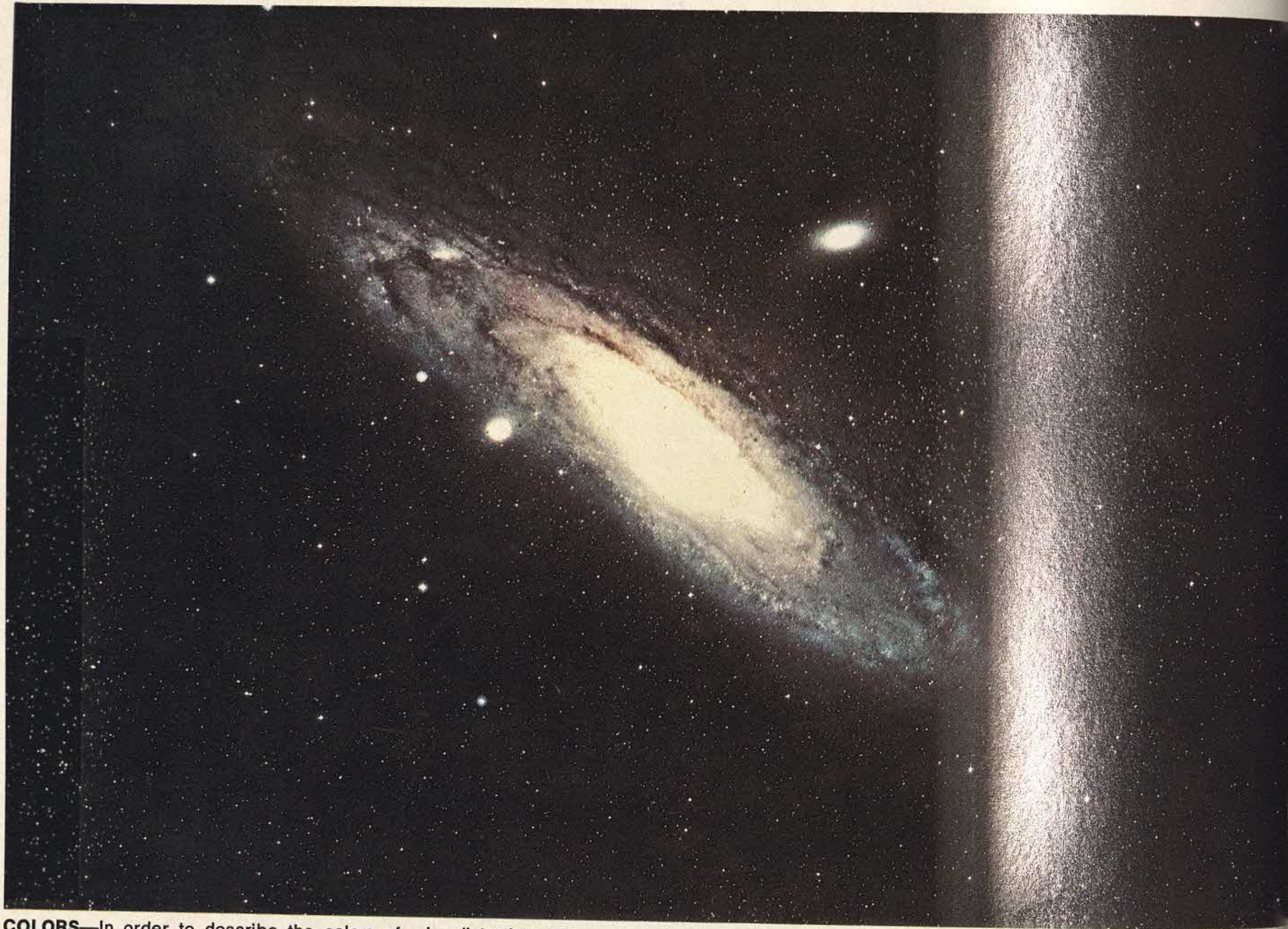


stars of population type II, with the same characteristics, for the most part, of the stars in NGC 205, including many red stars. Only in the peripheral areas of this nucleus of population type II stars is the galaxy obscured by interstellar matter, appearing in the picture as black bands around the nucleus. Beyond these bands are well-separated stars of population type I, generally quite luminous and interspersed with interstellar material.

Illustration 1c exemplifies a galaxy almost completely composed of stars of population type I. This is the galaxy of the constellation Triangulum, near the Andromeda galaxy. The arms of its spiral are quite open, with an abundance of stars and star clouds. The latter, appearing as large, dark patches, indicate the presence of interstellar matter and are indicative of a recent, or at least not well advanced, stage of evolution. The stars of the spiral arms are luminous and blue in color; the extremely small nucleus, like that of the nucleus of Andromeda, has stars of population type II.

In configuration, groups of stars of population type I are typically irregular; those of population type II are regular and symmetrical.

2a



COLORS—In order to describe the colors of stars with any accuracy, it is best to use black-and-white photography with filters rather than color photography. Color photographs furnish some information, but account must be taken of luminosity factors that may result in distortion. The color photographs shown here are of the Andromeda and Triangulum galaxies (Illustrations 2a and 2b, respectively). The most outstanding characteristic of the Andromeda galaxy is its color distribution, blue in the peripheral areas and yellow toward the center. The film used in taking the photograph is extremely sensitive to color differences, and what would normally have appeared as a decidedly red tint, toward the center, appears white because of excessive exposure. The white appearance of the com-

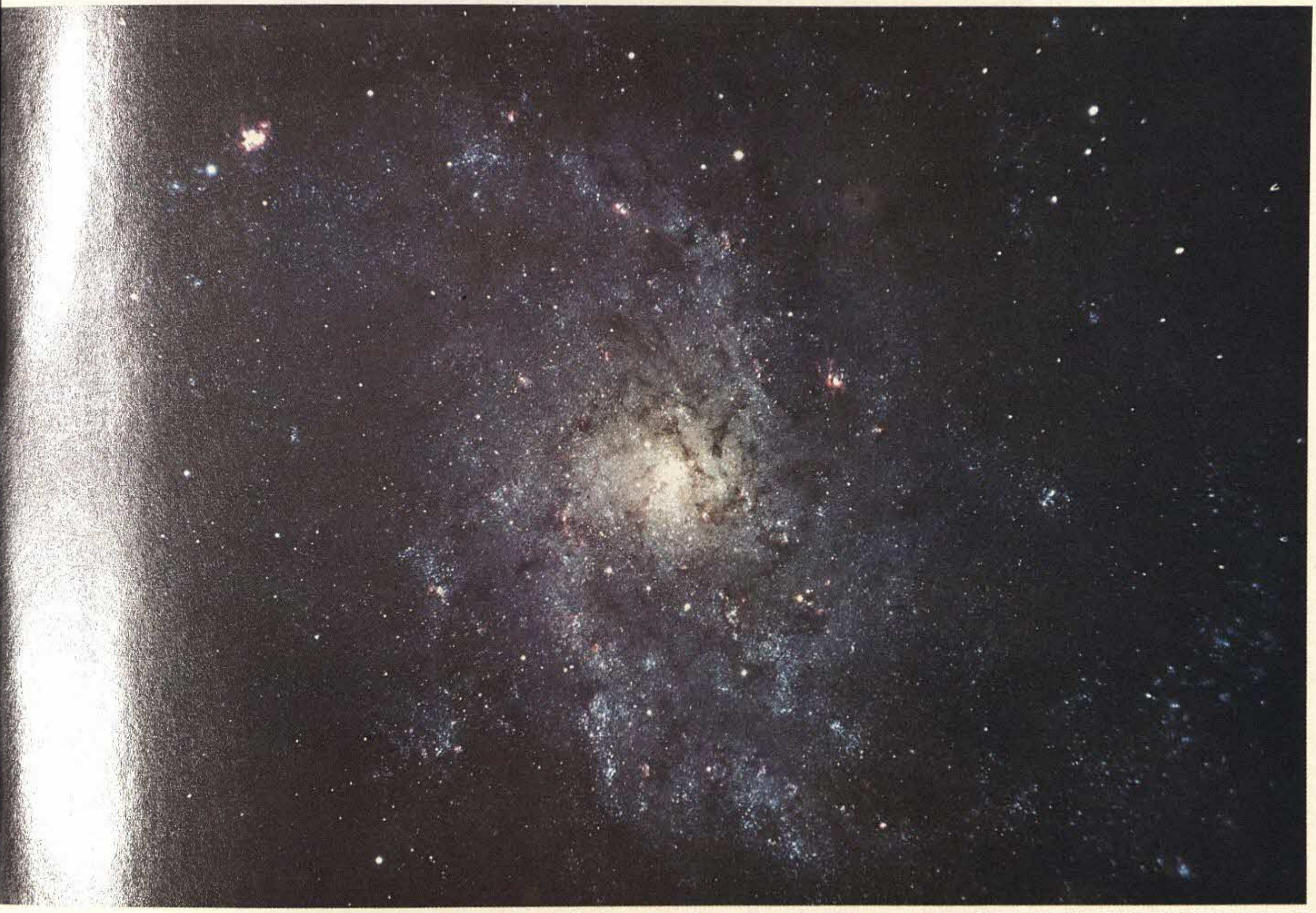
which stars are identified.

Observation of the stellar systems, therefore, suggests that stars may be divided into categories, and more thorough examination makes classification even more precise. Analysis of a statistical sample of the stars of a globular cluster, for example, reveals an extremely close resemblance among them. The same analysis of the stars of another cluster reveals a comparable resemblance among them, but slight differences from the stars of the first cluster. In other words, the stars of a given cluster are so uniform that two clusters apparently similar on superficial examination will prove, under more thorough analysis, to have considerable differences between them.

On a more practical level, it is possible to make extremely interesting observations by studying the compositions of many celestial objects: the star clouds of the Milky Way, stars of other galaxies, and stars of the clusters. This study will demonstrate the tendency of stars of similar characteristics to occur in groups. An analysis of these characteristics will suggest that they relate to the evolution of the stars.

Some stars, for example, reveal that they originated in recent time—meaning, on the astronomical scale, within the

2b

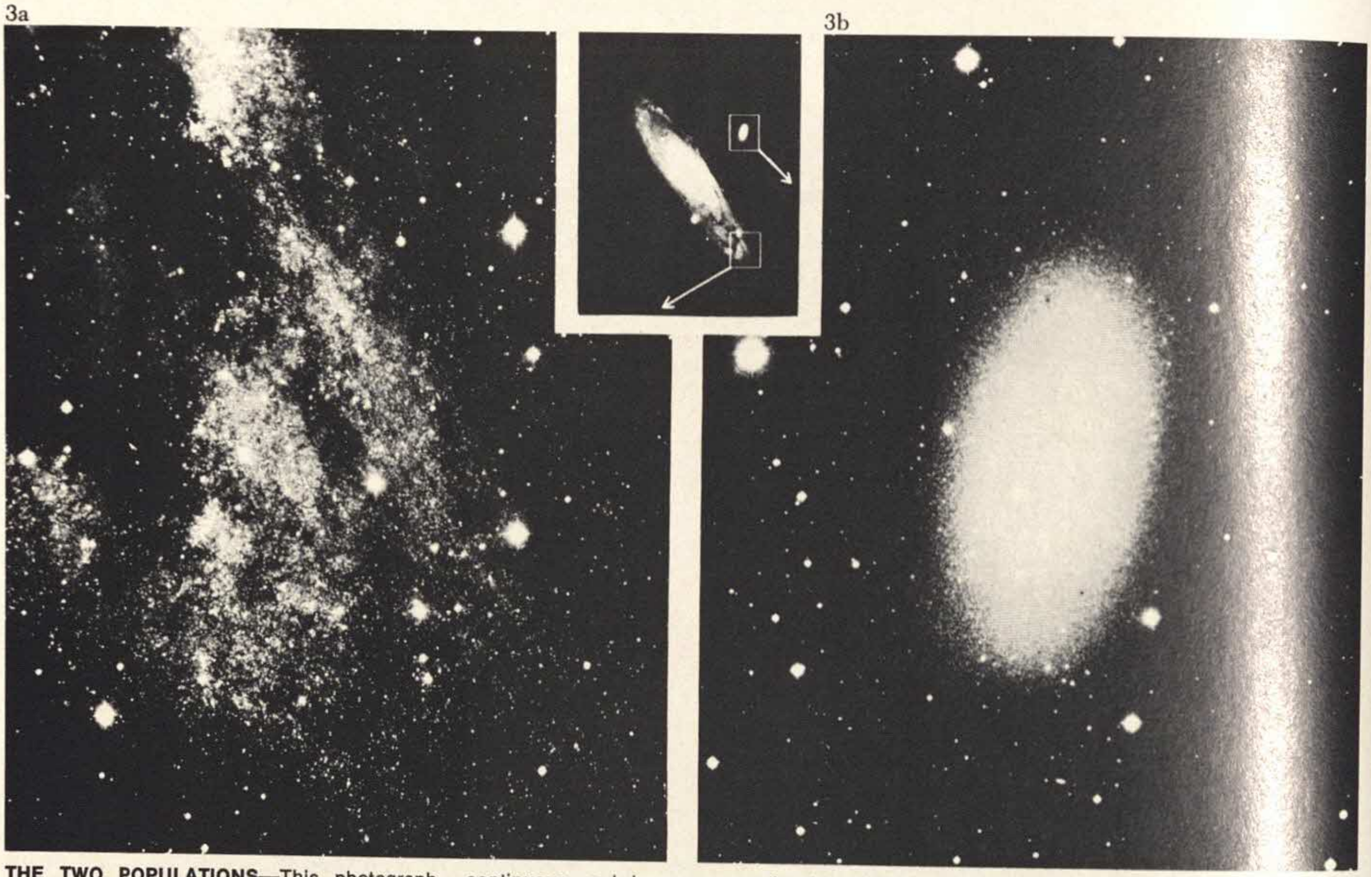


panion galaxy NGC 205 (above and to the right of Andromeda) is caused by the same excessive exposure, and would otherwise have appeared red.

The galaxy M33 of Triangulum (Illustration 2b) has the characteristic of being almost uniformly luminous, so that color film shows the tints of the stellar populations well separated. Therefore, all the stars appear bluish except for those appearing in front of the central luminous area; these stars, of population type II, have a color in the yellow-orange range. The purplish color of some gaseous nebulas containing radiations of hydrogen atoms is caused by the simultaneous presence of blue and red spectral lines. Fundamental measurements of stellar magnitudes and colors are now made by photoelectric photometry.

past million years or even tens of millions of years. The celestial regions populated by such young stars have other characteristics besides those pertaining to the physical nature of the stars themselves; for example, they are often permeated by diffuse gas or by interstellar matter in the form of fine dust, and the distribution of the stars within these regions is quite irregular. In other celestial regions, on the other hand, are stars that are astronomically old, very similar to each other, tending to form groups rather regular in shape, and with no interstellar matter in the space between the stars. Regions of these two types are said to contain stars of different populations: those of the young stars with population type I, those of the old stars with population type II. This division is far less subtle than the distinction previously mentioned between the stars of two globular clusters; but it suffices to classify the stage of development of certain stellar systems, as can be observed in studying some galaxies. The concept of stellar populations was introduced into astrophysics about thirty years ago, and is very important in tracing, in an approximate manner, the evolution of a stellar system, as some examples of galaxies illustrate.

The term *astrophysics* is of relatively



THE TWO POPULATIONS—This photograph shows the basic difference between the two categories of stellar population. The significance of the difference is enhanced by some details concerning procedures followed in taking the photograph.

In the center is a panoramic picture showing the limits of the two regions illustrated in the enlarged photographs on each side, the area of which is enclosed in rectangles in the inset. In Illustration 3a is shown a fringe area of the Andromeda galaxy. In Illustration 3b is shown, on the same scale, its satellite galaxy, NGC 205. The very bright stars that appear in what may be termed the foreground are stars of the Milky Way, occupying positions in space between the camera and Andromeda, and unrelated to the subject.

In Illustration 3a, the galaxy, which appears continuous and homogeneous in the panoramic inset, is broken up into a large number of quite luminous stars distributed in a relatively irregular way. The photograph was taken through a blue filter; the stars that appear in the picture are blue giants, and they are stars of population type I: luminous, hot, and in a state of rapid revolution that is transforming their initial characteristics.

In Illustration 3b, the companion of the Andromeda galaxy, so called because it stays close like a satellite, is shown in its entirety, photographed through a yellow filter. The stars, of population type II, are all weak, yellow or orange, close to one another, and distributed with great regularity.

It is possible now to compare the stars of the two populations. The most luminous stars of population type II are many times less luminous than those of population type I. If the panoramic shot of the inset is observed from a distance of a yard, the scale would appear about the same as that of the galaxy under direct observation in the night sky, whereas the two side pictures are greatly enlarged. However, it is impossible, either by direct observation with the naked eye or by direct telescopic observation, to see the same number of stars or to see them with the same luminosity as can be seen in these photographs. The photographic plate can accumulate the starlight for an extended exposure, whereas the eye can react to the light only for the instant of perception and cannot accumulate the light over a long period of time. For this reason photography is absolutely essential for a study of stellar populations.

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recent origin, but the study of astrophysics—a science concerned with the physical properties of the celestial bodies—began long before the middle of the nineteenth century. The most spectacular development since 1950 has been the unraveling of the principal processes of stellar evolution and the recognition of evolutionary tracks of the stars in the Hertzsprung-Russell diagram.

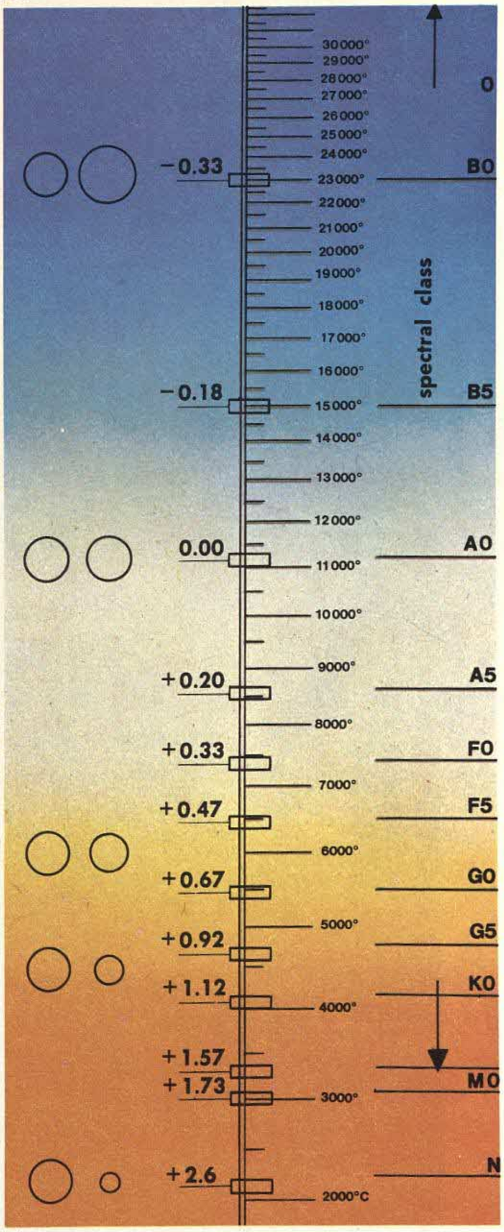
In the next stage of astrophysics, it is expected that the development of space science will bring a reversion to the character of the first stage—the accumulation of many new and unexpected observational results and discoveries such as have already been made by means of high-flying rockets. These discoveries have given totally unexpected data on the extreme ultraviolet spectrum of the sun and of a few hot, bright stars and on the existence of luminous hydrogen atoms in interplanetary space. It is expected further that methods will be developed for recording systematic evolutionary changes in a few individual stars. If a star should ultimately become a supergiant, it must increase in radius and volume. The change in radius cannot be measured directly, because it is much too small to be detected after intervals of hundreds or thousands of years. But if such a stars vibrates, then as the volume increases the vibration period should lengthen; and it will be possible to measure that period with great precision.

THE HERTZSPRUNG-RUSSELL DIAGRAM | a register of the stars

1a

1b

1c



COLOR INDEX—Basic to an understanding of the Hertzsprung-Russell diagram is the color index, used to define the color of a star, from which its temperature can be deduced.

In any photograph of the celestial sphere (illustrations 1a and 1b), stars appear as disks with shadowed outlines, and of greater or smaller dimensions according to their apparent luminosity. However, if this photographic luminosity is compared with the apparent brightness of the same stars when observed visually, it is quickly apparent that some of the stars that are barely visible to the eye are extremely brilliant in photographs. Conversely, some stars that are almost invisible in the photographic image are luminous to the eye.

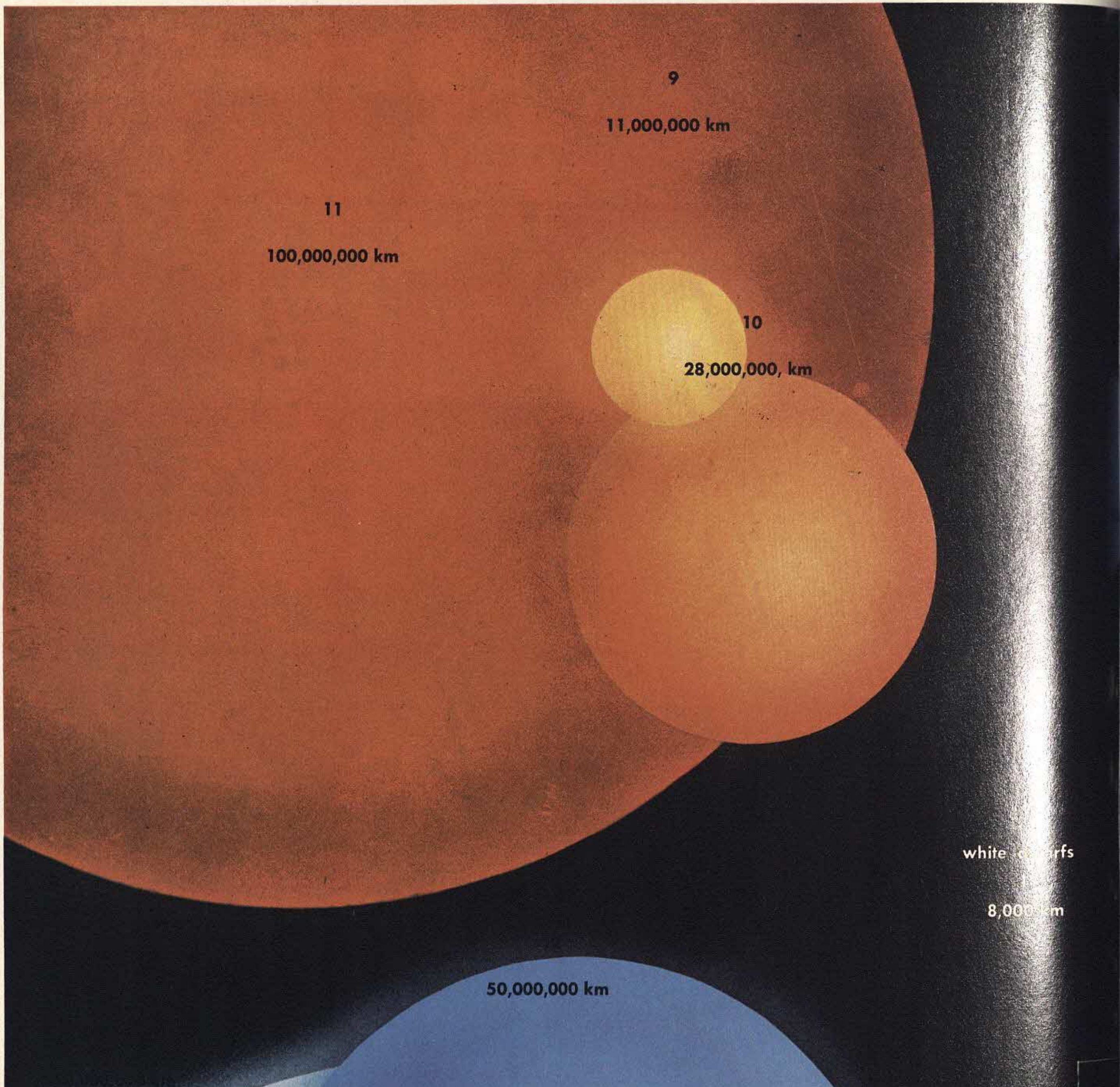
The explanation of this phenomenon lies in the fact that stars shine with a colored light. They behave in the manner of Max Planck's black bodies; their temperatures determine the colors they emit—colors ranging from red (for the lower temperatures) through yellow, white, blue-white, to blue for the hotter stars. Conventional film is predominantly sensitive to blue and practically insensitive to red and yellow. Therefore, blue or blue-white stars show up less brilliantly to the eye than on a photographic plate, while those emitting red or yellow light appear less brilliant when photographed.

Photographic emulsions have been developed that have the same sensitivity to color as the human eye, producing an image of the sky similar to that which the observer actually sees. Nevertheless, astronomers find it useful to determine the color of stars by analyzing the difference in stellar magnitude that they display when observed visually and when observed by means of film sensitive to blue. It is not necessary to complete a photographic as well as a visual measurement however; two photographic measurements—one made with film sensitive to blue and the other with film sensitive to red and yellow through a red filter—are equally effective.

The difference in stellar magnitudes—revealed first by film sensitive to blue and then by film sensitive to red—is known as the color index. A red star, whose magnitude is expressed by a high number on the scale, appears weaker in the film sensitive to blue. Therefore, the color index of a red star is positive, while that of a blue star is negative. Stars of the spectral class A0 have a color index rating of zero, indicating the relationship that binds the absolute temperature of these stars to the color index. From this point, the scale goes up or down, depending on color. Starting at O position, the negative values of blue stars never reach high numbers: −0.3, for example, is an exceptional value for a blue star. On the other hand, red stars frequently have a color index rating of +2.0 or greater.

Illustration 1c shows the scale of the color indices and the temperatures corresponding to them. On the left are the graduated values of the color indices. The paired circles indicate the relative difference in luminosity between a specific star as photographed and as observed visually. The circle on the right represents the size of the star as it appears in photographs; the left circle represents it as it appears visually. On the right side of the diagram is the temperature scale with a color band representing the color of a star's light as observed by the eye.

By use of a simple formula, the value indicated on the color index can be employed to determine the surface temperature of a star. This formula is: $T = 7{,}200°/(I + 0.64)$, where I is the color index, 0.64 a correction factor, and T the temperature in °C of the stellar photosphere. On the basis of this formula, stars of spectral class N, of color index +2.6, have a surface temperature lower than 2,200°; those with a color index of −0.33, of spectral class B0, have a temperature more than ten times greater, 23,000°.

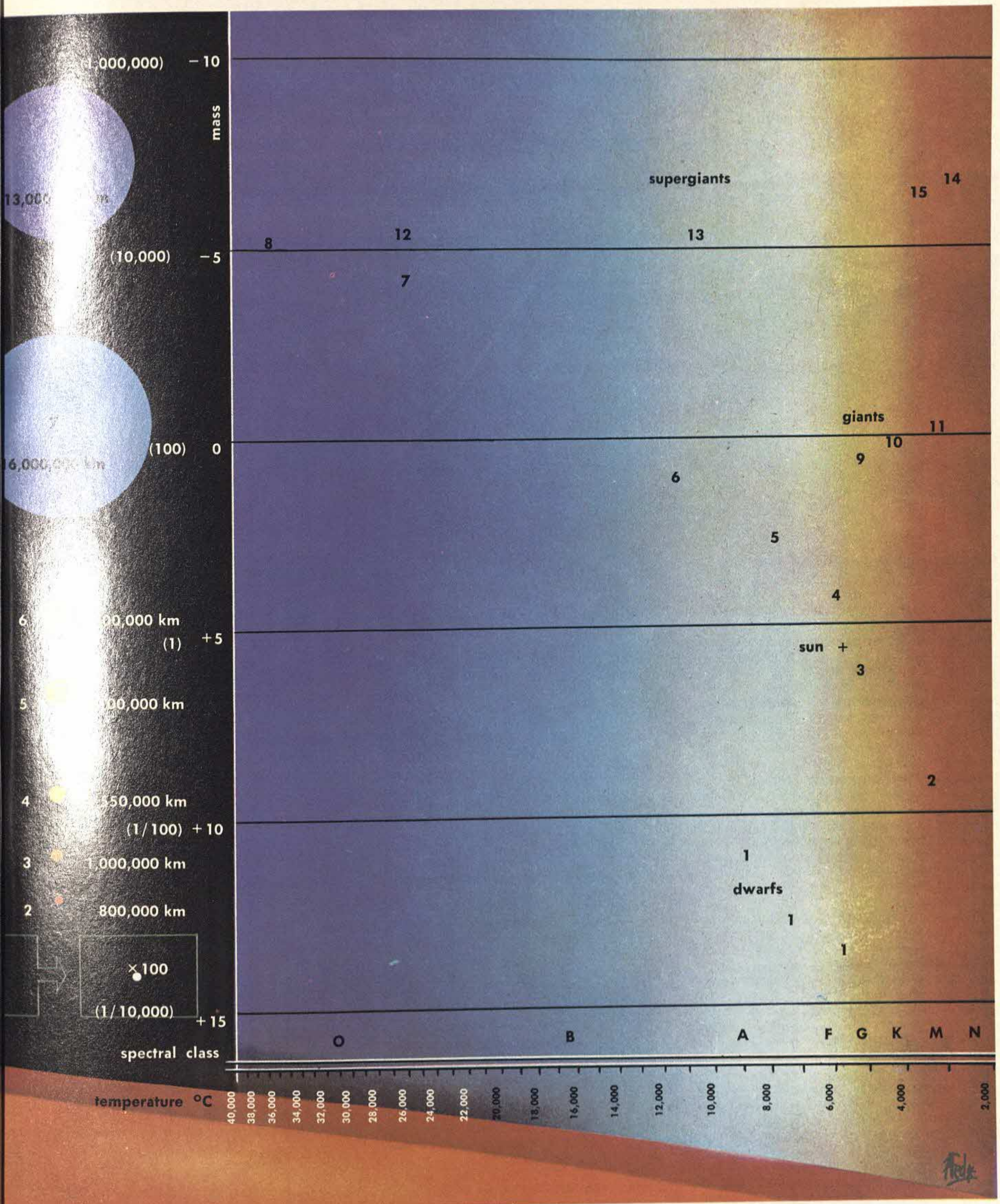


LUMINOSITY, BRIGHTNESS, TEMPERATURE, COLOR, SPECTRUM, DIAMETER, MASS—In this illustration, all the properties of the stars that are placed in the various parts of the Hertzsprung-Russell diagram have been grouped together.

The properties of the stars are so variable that it is difficult to illustrate them all in a single table. Here, variation in spectral class has been interpreted by variation in color—an easily represented characteristic for all stars.

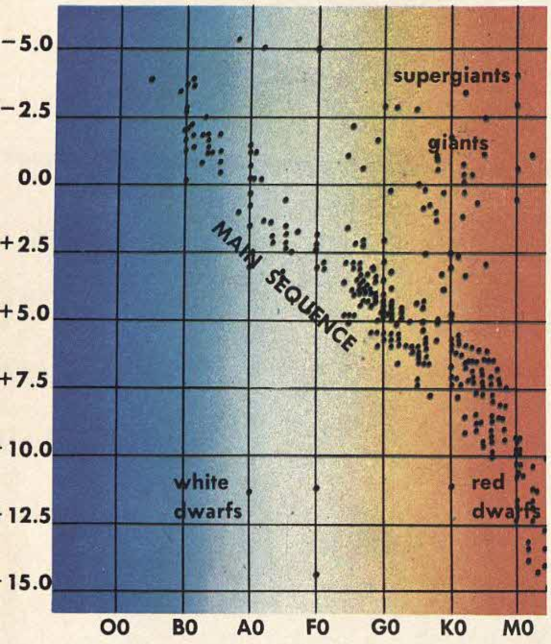
Variation in absolute luminosity is indicated on the vertical division of the scale. It extends from values equal to about 1/10,000 to values 1,000,000 times the absolute luminosity of the sun, used as a basis for comparison.

Parallel to the variation in absolute magnitude is the variation in mass. Stellar masses vary less than absolute luminosities even though the variation is strictly correlated. For example, a mass ten times less than that of the sun corresponds to a luminosity 10,000 times less than that of the sun, and a mass ten times greater corresponds approximately



to a luminosity 10,000 times greater. In other words, there is a definite relationship between mass and luminosity, even though luminosity stretches over a wide range while variation in mass is much narrower.

If stellar diameters varied only to a small degree, they could be represented by circles of different diameters. However, the variation in stellar diameters, from the dwarfs to the giants and supergiants, is so great that, in the case of the giants, it has been necessary to represent only a portion of the stellar disk, and to introduce a variation in scale corresponding to the white dwarfs. The supergiants have diameters of millions of kilometers; some of the dwarfs, on the other hand, are as small as the Earth. For the larger, nongiant stars, diameters of a value of several meters have been adopted for this diagram. Using this value, however, the illustrated diameters of the smaller stars would have been approximately 0.1 mm. Therefore, where indicated, the scale has been enlarged to represent the smaller stars.



THE LUMINOSITY-SPECTRUM DIAGRAM— In this illustration, the luminosity-spectrum diagram is shown for a limited number of stars. They range from spectral class B0 to N. Most of the stars that are closest to the solar system are distributed along the descending diagonal, which is slightly S-shaped, with only the central portion straight. The star group around the principal diagonal is known as the main sequence and includes most of the stars in the universe. For example, the sun—of class G0—is situated almost at the center of the main sequence. The stars at the bottom are generally known as dwarfs because of their small dimensions, while the large stars at the top are known as giants. Some stars are outside the main sequence. Some are so far out that their representative points lie toward the lower left corner. These are stars of weak luminosity, with a small mass and diameter. Since they are of the first spectral type—white or blue-white—they are known as white dwarfs.

Another group of stars is located between the main sequence and the upper right corner. These are the giants, or red giants when they are of an advanced spectral type.

Finally, a very few stars are situated along the upper edge of the diagram. They belong to the highest stellar order—the most luminous stars known—and are known as supergiants. The horizontal band where they are situated is known as the band of the supergiants.

The vertical scale of the diagram is divided linearly according to increasing values of absolute magnitude, which extend from +15 to about −7.5. Some stars vary almost between these two extremes, with luminosities differing by more than 20 stellar magnitudes. For example, the difference in the magnitude of stars at either extreme is greater than the difference between the light emitted by a lighthouse and a firefly.

During the latter part of the nineteenth century, astronomers generally subscribed to the theory that stars were celestial bodies with dimensions comparable to those of the sun. Despite many advances in astronomical knowledge, science at that time did not possess the capabilities to conduct an accurate study of the distant stars. It was not possible to measure the dimensions of stars, nor could their other characteristics, such as absolute luminosity or surface brightness, be scientifically determined. Methods developed early in the nineteenth century by the German astronomer and mathematician Friedrich Wilhelm Bessel were sometimes used to measure stellar distances with a certain degree of accuracy, but such measurements were not sufficient to establish reliable statistical data.

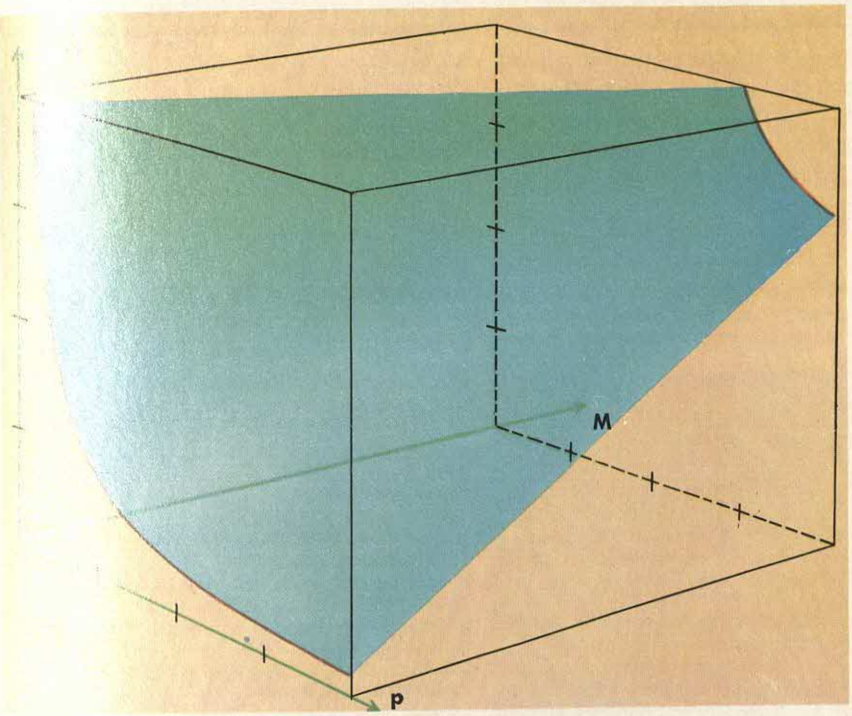
During the first two decades of the twentieth century, two astronomers—Ejnar Hertzsprung, a Dane, and Henry Norris Russell, an American—provided the foundations of present-day knowledge of astrophysics and stellar astronomy. At the time Hertzsprung and Russell were beginning their pioneering work in the early 1900s, it was possible to measure stellar distances by using the method of parallaxes. In this way, astronomers could determine many of the fixed characteristics of the closer stars and calculate their diameters and surface brightness. Yet man's knowledge of the stars was generally limited to the early studies of radiant energy by such scientists as the German physicist Max Planck. From these studies, it was determined that stellar matter behaves in a manner similar to a black body, in which determination of the surface temperature makes possible the subsequent calculation of the flow of energy and other characteristics. Thus, the solution to the problem of scientifically analyzing stars began to take shape: first, establish the color of light emitted by a star in order to determine the surface temperature; and, second, after the absolute magnitude of the star is established, calculate its surface area and diameter.

This theory of radiation led to a widening study of the structure of stars and the beginning of a scientific classification of their characteristics—a monumental undertaking spearheaded by Hertzsprung and Russell. In 1905 and 1907, Hertzsprung published papers demonstrating the relationship between the color of stars and their true, or absolute, brightness. He established a sequence of brightness, ranging from the blue and white stars through the yellow, orange, and red. Hertzsprung also pinpointed such yellow, orange, and red giants as Arcturus, Aldebaran, and Pollux.

While Hertzsprung was developing his brightness sequence, Russell was working at Princeton University on investigations in almost every field of astronomy and spectroscopy. In 1913, he produced a diagram that set forth in graphic form the spectral types of stars in order of their absolute magnitude. Russell's diagram, illustrating the relationship between surface temperatures and the absolute magnitudes of stars, attracted wide attention in the world of science.

In Germany, where he was teaching astronomy at Göttingen, Hertzsprung expanded on Russell's work, developing the Hertzsprung-Russell diagram, which today is still recognized as the fundamental description of stellar types. In establishing a relationship between the strength of certain properties of the spectrum of a star and its true brightness, Hertzsprung and Russell made it possible to estimate the true brightness, or absolute magnitude, of stars by analyzing the appearance of a stellar spectrum. Their luminosity-spectrum diagram is rightly considered a significant milestone in the history of astronomy. The diagram not only placed the stars in order of their luminosity and spectral type, but also rated them on the basis of color index, surface temperature, and mass. The diagram clearly showed that all of these stellar properties were closely related. As a result, when the spectral type of a star is established, it is also possible—by plotting its position in the diagram—to determine its diameter, surface temperature, mass, and absolute luminosity. Development of the Hertzsprung-Russell diagram made it possible to construct a model of the structure of stars, from which evolved an interpretation of their internal characteristics. In brief, the diagram was the starting point for today's theory of stellar structure.

THE STRUCTURE OF STARS | from simple hypotheses to advanced theory



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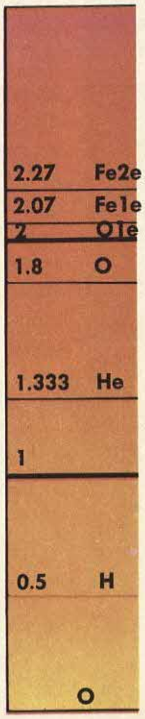

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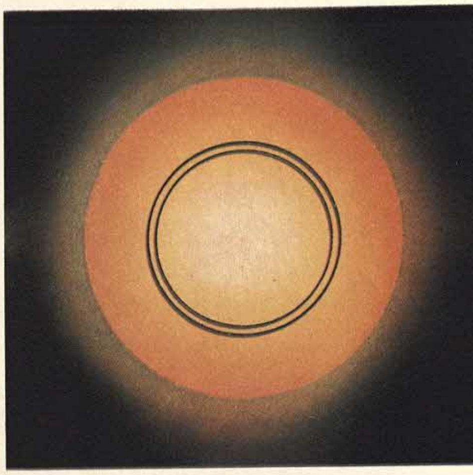


STELLAR GAS—A model of a stellar structure cannot be built without a knowledge of the material of which the star is composed. However, through spectral analysis, all the component elements are known. Nearly all stars are predominantly composed of hydrogen, although other elements are present. Even when the chemical composition is definitely known, however, it is necessary to formulate a hypothesis about the state in which this matter occurs. Inasmuch as the temperature at the surface of the stars is of the order of thousands of degrees, and because the flow of energy from the interior to the exterior requires an even higher temperature at the interior, it follows that all the elements must exist in an ionized state. Hydrogen must have lost its single electron, and the other elements must be composed of atoms ionized to a greater or lesser degree according to the temperature.

This, then, is the first important property of the stellar gas. It is composed largely of ionized hydrogen; and because the volumes of the hydrogen proton and electron are negligible when compared with that of the hydrogen atom, the gas composed predominantly of ionized hydrogen must be extremely dense. Moreover, the forces in effect between the particles of such a gas (protons and electrons), although far greater than those in effect among the atoms, are negligible when compared with the force with which the atoms themselves are colliding. The average mass of the particles of which the gas is composed is midway between the mass of the component atoms (from the chemical point of view) and the mass of the electrons expelled from each atom. Thus, the average molecular weight of the gas can be used to predict its behavior just as though the gas were composed of a single atomic substance—although it is not composed of a single substance, and is not even composed of atoms, but rather of a mixture of particles that differ from atoms. It is nevertheless possible to apply the law for a perfect gas to the study of stellar gas, providing that the average molecular mass—as indicated, halfway between that of the atoms and their electrons—is used in place of the single molecular mass of a nonionized gas.

Illustration 1a is a three-dimensional representation of the gas law. Its formula, as used in the study of stellar structure, is $p = R\rho T/m$, where R is the well-known gas constant, ρ is the density, T is the absolute temperature, and m is the average mass. (M is the total mass of the gas.) The relationship between density and average mass is used in place of volume, for while the volume of a gas is significant in the laboratory, density is significant in the case of a star.

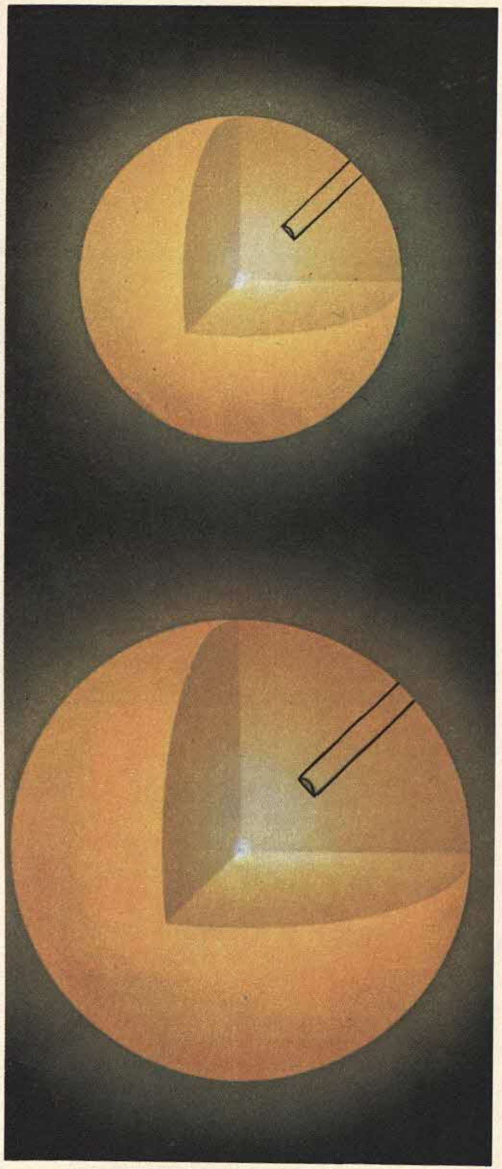
The average masses of ionized gases are shown in Illustration 1b. When hydrogen is completely ionized, for example, its average atomic mass is exactly 0.5. (The weight of the electron is negligible compared with that of the proton.) Elements with greater atomic weight, and hence with more electrons, may have different molecular weights, depending on whether the atoms have lost all their electrons or have retained the last one or two near the nucleus (these latter electrons are much more difficult to ionize than the outer electrons). It must always be remembered that hydrogen is by far the predominant component of stellar gas, and that the percentage of other components, even if these are highly ionized, will make little difference in the average molecular weight of the total stellar gas.

THE EQUILIBRIUM OF A STAR—The initial hypothesis must always be that the star is spherical and is in equilibrium—regardless of the law of increasing density or temperature in the direction of the star's core, regardless of the density of stellar gas, and regardless of other factors. This means that in any section of a star (as shown in Illustration 2) this law applies; if an infinitely thin crust is cut within a star, every element therein has a mass corresponding to the attractive force of gravity determined by the stellar mass contained within that crust. In this case the pressure within the crust should equal that just beyond the crust, with the addition of the weight of the layer of crust itself.

The hypothesis of thermal equilibrium is also essential; it is assumed that at each instant the flow of thermal energy occurs throughout the star from the interior to the exterior and at a constant rate. As in every body, thermal energy is transferred by radiation, conduction, and convection. Conduction is negligible. Convection is important only in particular stars, such as the white dwarfs, the density of which is so great that the movement of even a small amount of matter involves the transfer of considerable energy. In most stars, however, transfer by convection is insignificant. Only radiation can account for the centrifugal movement of thermal energy.

The law of density as a function of depth in the case of stars is basically comparable to the hypsometric law of the Earth's atmosphere; that is, the law of density as a function of altitude. In the case of the atmosphere, however, the procedure is much easier, because the laws followed by the gases of the atmosphere are much simpler than those followed by stellar gas.

3



THE PROPERTIES OF HOMOLOGOUS STARS—One of the first objectives in studying the composition of stars is to determine the law according to which density within stars increases in the direction of the stars' centers—an objective not yet completely attained. One approach is to study the properties of homologous stars—those that are alike in respect to increasing density but that differ in diameter and other properties. Thus, two stars with different diameters, each having identical density at one third of the radius from the center, are homologous stars. Any two points in homologous stars that are distant from the center by the same percentage of the radius are said to be correspondent.

The properties of homologous stars were deduced in 1870. At correspondent points inside of homologous stars the density varies as M/r^3, the pressure as M^2/r^4, and the temperature as mM/r. (M is the mass, r the radius, and m the average molecular weight of gas at the point under consideration in the star.) If only the radius changes, the density varies as $1/r^3$, pressure as $1/r^4$, and temperature as $1/r$.

Illustration 3 shows sections through two homologous stars. If the two columns of gas indicated within the stars extend to depths beneath the surface that are the same percentage of the radii of the two stars, the two sections must also be in proportion.

At the end of the nineteenth century, physicists acquired the theoretical capability to deal with the question of the composition of the stars. In the first decade of the twentieth century they discovered the enormous reserve of energy within the atomic nucleus; at this same time the laws concerning the behavior of gases and the laws of radiation were formulated. Not much was known about ionization or the structure of the atom, but enough was known to determine the structure of the stars.

At that time stars were known to be spheres of gas that could best be analyzed spectroscopically. It was known that their temperatures were in the order of thousands of degrees and that they were sometimes as dense as the sun, but sometimes much less or much more dense than the sun. It was also known that stars were sources of enormous amounts of energy, the origin of which was not yet determinable but which was probably related in some way to radioactive decay. (No model of nuclear structure existed at this time, and radioactive decay was the only kind of change known within the atomic nucleus.)

The problem was attacked by accepting a few simple hypotheses, which later proved to correspond fairly well with reality, and which led to a theory of stellar structure. One of these hypotheses was that the inner core of stars, very small in comparison with the total volume of the star, was the source of energy, but that the gaseous sphere of the star around

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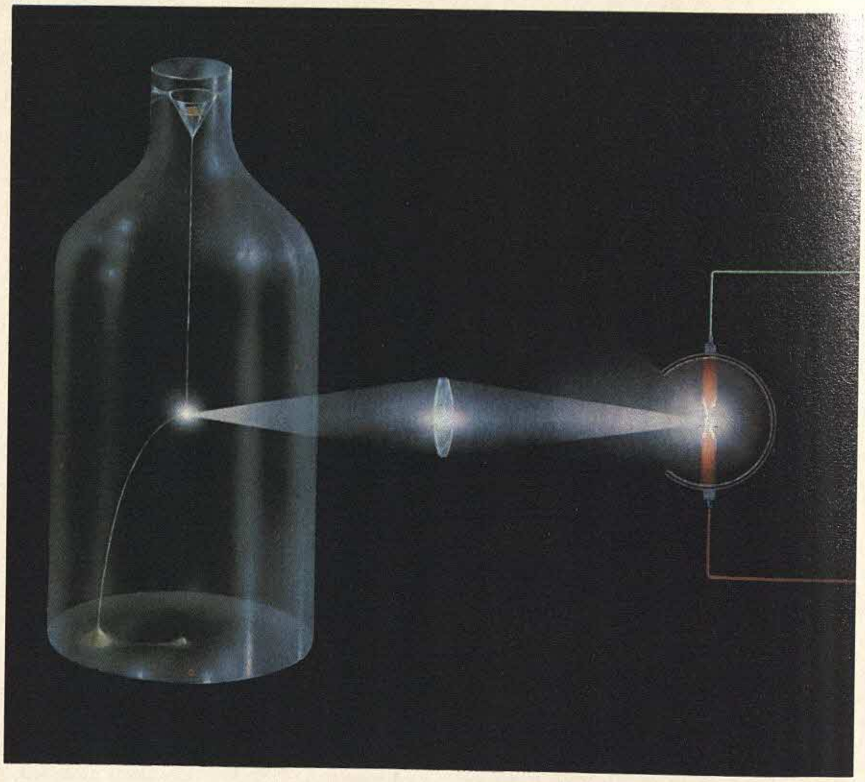
THE PRESSURE OF RADIATION—Pressure in the interior of a star is determined by the law according to which density increases in the direction of the center, and also by the diameter of the star. The pressure in the interior of a star is enormous; at the center of the sun it is 36 billion atmospheres (1 atmosphere = 14.7 lb/sq in.). Almost all of this enormous pressure is sustained by the pressure of radiation.

The pressure that light exerts on a body can be shown in the laboratory experiment illustrated here. A very fine powder is dropped into an empty container. In the dark, the powder falls vertically; but if a powerful beam from an arc light is directed toward the falling powder, the grains are deflected. The amount of deflection, even using a very powerful arc light, is slight because light exerts relatively little pressure; but in the interior of stars the pressure of radiation is very strong, increasing as the fourth power of the absolute temperature of the black body that emits it. Inasmuch as the temperature in the center of a star reaches tens of millions of degrees, the pressure of radiation reaches tens of billions of atmospheres.

4



this core must be studied as if this core did not exist. It was also assumed that stellar gas behaves as a perfect gas. Finally, it was assumed that stars are spherical and in a state of equilibrium. These hypotheses can be assumed to pertain to all stars, with appropriate modifications—for example, the case of a star that is ellipsoidal because of its rotation, or a star that is contracting or expanding because of some instability.

Using such simple hypotheses as points of departure, it is possible to construct a theory of the composition of stars–that is, a theory involving laws and formulas according to which certain data will indicate the characteristics of a given star. For example, if the mass and surface temperature of a star are known, it might be possible to determine its absolute luminosity; if its constants are known, its diameter may be determined. The English astrophysicist Sir Arthur Stanley Eddington worked out the fundamentals of the theory, revealing new horizons in astrophysics–for example, the measurement of spectroscopic parallaxes, the laws that govern the evolution of stars, and the investigation of anomalous or unstable stellar structures.

In 1916 Eddington began the fundamental researches that led to the creation of the present-day theory of the internal constitution of a star. His crucial hypothesis was that the energy emitted as light and heat from the stellar surface was transmitted throughout the interior in the form of radiation also. He concluded that most stars are gaseous throughout, and he made the major discovery that the mass and the luminosity of a star are related.

Some of the fundamental principles on which the study of stellar structure is based and the ways in which they can be applied to the structure of different types of stars are shown in the accompanying illustrations.

THE MODEL OF A STAR—If a sphere of stellar gas is in equilibrium, with its core producing energy and its surface dissipating energy (the transfer of energy taking place by radiation), and with the hydrostatic pressure maintained principally by radiation pressure, very significant formulas can be derived to describe the physical conditions that regulate the sphere's composition. It is necessary to have other data to start from—for example, the molecular weight of the gas composing the sphere—but the problem is easily solved despite the complexity of the calculations.

Under these conditions and given these premises, the stellar gas may be expected to remain in equilibrium only so long as the relationship between the temperature and pressure in the core can counter the hydrostatic pressure with radiation pressure; the entire system depends on the total mass and the diameter of the star.

The illustration shows the section of a star in which the atoms are depicted as cylinders a open at each end but divided by a central diaphragm. Radiation can enter at one end but must pass through the diaphragm to leave the other end. Each cylinder, therefore, acts as a kind of retarding element to the passage of radiation. Each atom is subject to the impact of radiation, which would not be active if it could pass freely. Whatever the mass and diameter of the star, it must come to have a stable luminosity depending on the pressure in the interior, and this in turn depends on the temperature.

Supposing that this model is valid for the sun—and assuming as the correct values for average molecular weights that of oxygen as 2.0, of iron as 2.2, of silver (as an example of a heavy atom) as 2.4—the density at the center is 28, the pressure 36 billion atmospheres, and the temperature 29 billion° C. The equations involving these measurements contain very high exponential factors, so that a small variation in one measurement could cause a great variation in the values of the others. The model may be described as sensitive to prevailing conditions, and these must be clearly understood or hypothesized if the model is to indicate accurately the properties of a star.

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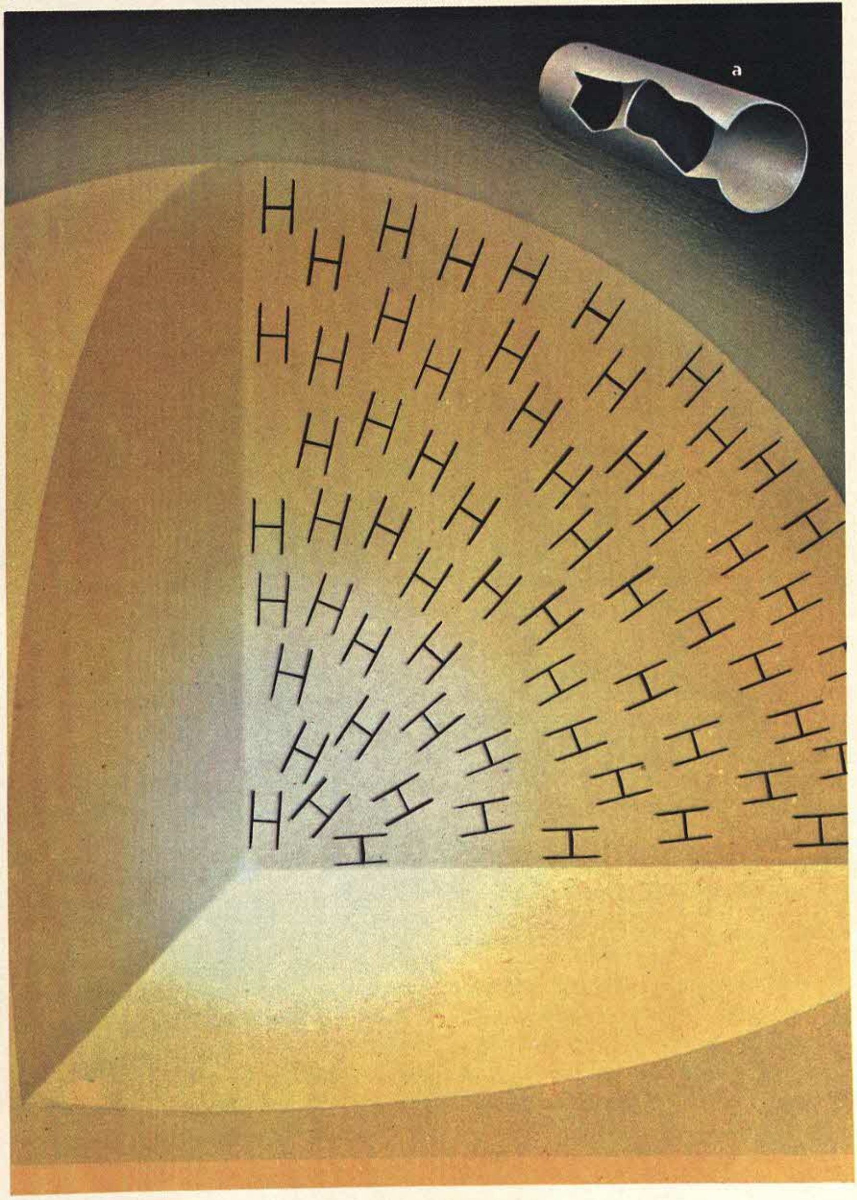
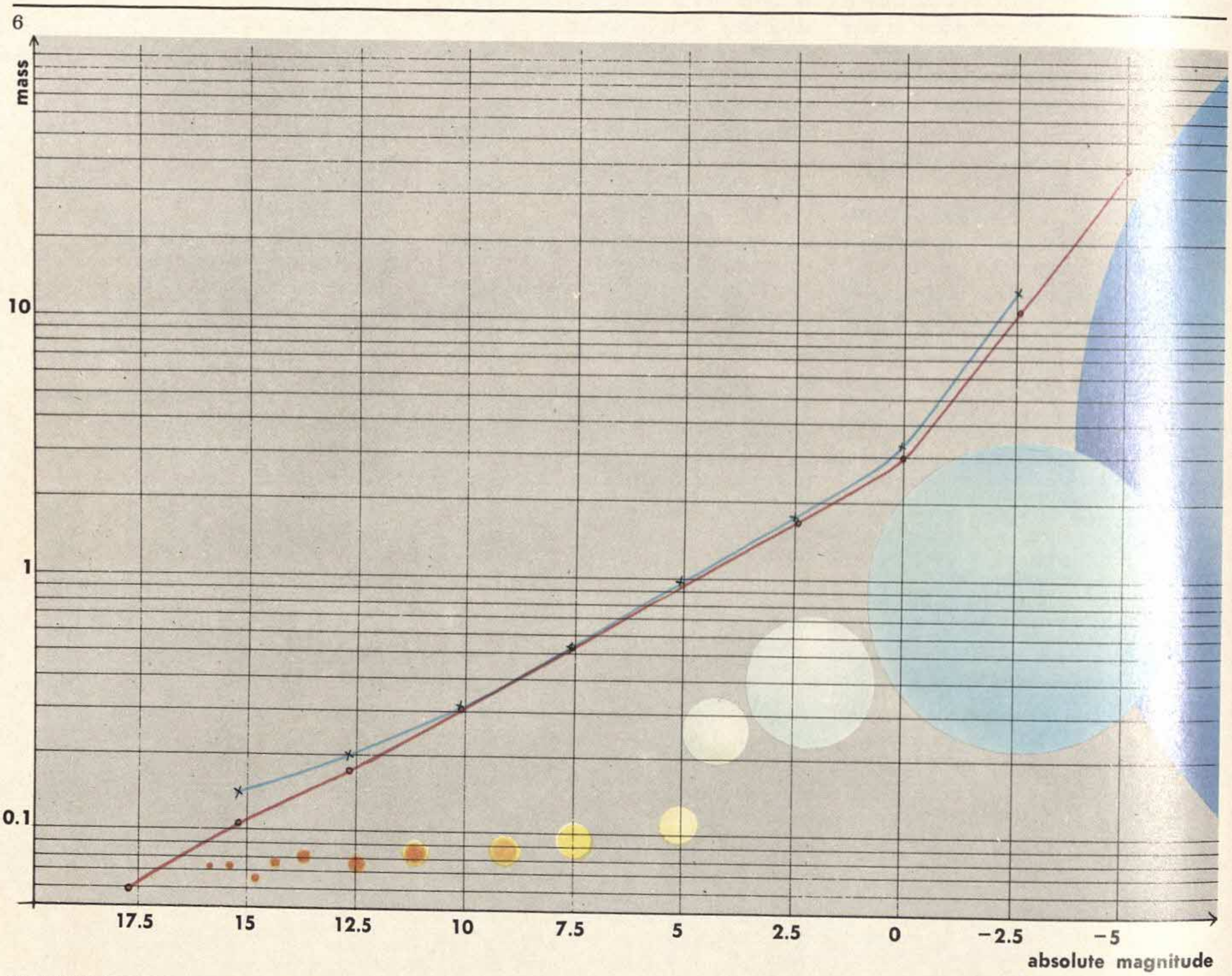




THE LUMINOSITY FORMULA—On the theory that stars are spheres of ionized gas in equilibrium, a model hypothesis can be formulated to show not only the temperature, pressure, and other conditions prevailing in the interior, but also the absolute luminosity of the star. Such an exact formula, based on the physical constants, shows in reality not the absolute but the relative stellar luminosity—that is, the difference in luminosity between a star of a known type and one with properties that are not all known: $A = A' - 3.75 \log (1 - \beta) - 3.5 \log M - 2 \log m - 2 \log t$. In this formula, A is the magnitude of the star whose luminosity is being sought; A' is the magnitude of reference; β is the percentage of pressure sustained by radiation pressure; M is the mass of the star expressed in units of the sun's mass; m is the average molecular weight; and t is the absolute temperature on the surface of the star.

If this formula is applied, first to a star for which many properties are known, then to a star having some properties in common with the first star and other properties different, the luminosity of the second star can be calculated precisely. Moreover, it is possible to define the relationships of stars of many different sizes with respect to their sizes rather than to their luminosities.

The graph shows how precisely, using this formula, the mass of a star of known type can be calculated. Along the abscissa the absolute magnitudes are plotted; along the ordinate the masses are plotted. The red lines represent values obtained by calculation and the blue lines are measured values. The various types of stars, from white dwarfs of supergiants, are shown.

THE EVOLUTION OF STARS | from cosmic dust to supernova

The formation and evolution of stars are among the most intriguing problems of astronomy. From the beginnings of astronomical science among the Greeks through the eighteenth century, attention was concentrated on the sun and the planets, particularly their origin, for this seemed the central problem; the early scientists had no notion of the relative insignificance of the solar system in the universe.

One of the earliest scientific theories of the origin of the universe can still be found in texts—the nebular hypothesis propounded independently in the eighteenth century by the German philosopher Immanuel Kant and the French astronomer Pierre Simon de Laplace. According to this famous theory, the sun was formed by the condensation of nebulous material; the planets were smaller bodies formed by portions of the same material that failed to unite with the bulk of the central sphere. This hypothesis has many imperfections; it does not explain, for example, why the planets should have been given a greater momentum in their motion than the sun—a fine point, perhaps, but enough to cause a scientist to reject a theory. The hypothesis has other points that validate the notion of nebular origins, and only in recent times have scientists been able to make the fine distinctions that have improved on the nebular hypothesis.

During the present century, the attention of astrophysicists has been drawn from the narrow area of the solar system by such research as the discovery of galaxies beyond the Galaxy to which the solar system belongs, by the classification of the various types of stars, and by the discovery of such celestial objects as quasars, pulsars, and neutron stars.

EVIDENCE—The study of stellar systems, the patterns of which indicate their age, is useful in explaining the evolution of the stars themselves. This photograph shows a galaxy in which the stars at the rim are young, whereas those in the center are old. This can be deduced from the shape and appearance of the spiral structure of the galaxy. By identifying the spectral classes of the stars, the "early" and the "advanced" types (as shown in the Hertzsprung-Russell diagram) can be distinguished as two different phases in the evolution of the corresponding stars. The difference in age shows up in the photograph in the color of the stars—the blue stars are the younger, the yellow the older.

NEW PERSPECTIVES

It was supposed, initially, that if the origin of the sun and planets could be explained, the origin of the universe would no longer remain a serious problem. Then it was believed that a thorough study of the stars would solve the problem of the origin of the universe. However, the more the nature of the stars was analyzed, the more obvious it became that the great differences discovered among them must also be significant in the evolution of the universe. Common sense would seem to suggest that a large, bright star is younger than a small, dim star. Such notions led to a theory of stellar evolution, and many observations were needed to interpret correctly the diversities among the stars, to classify the stars, and to relate all this to the evòlution of the stars.

The greatest help in this direction came from the analysis of such star systems as clusters, nebulas, and galaxies. Very recently astronomers have discovered celestial objects that might represent very early or very late stages in the evolution of stars. However, scientists are not yet certain just what quasars, discovered in the early 1960s, or neutron stars, actually do represent. Quasars may be the first evidence of a new type of energy source.

THE PROBLEM OF EVOLUTION

The question of stellar evolution was long distorted because so much emphasis was initially given to the role of the planets, including the Earth. As a matter of fact, the problem of the origin and evolution of the universe touches on many points, of which only parts are accessible to scientists. Of these, the first is the origin of space itself. The question must be raised: Is space necessary? Could there not be nothingness, instead? Or, to phrase it differently, why could there not be absence of space rather than space? The next question must be: If space must exist, why must it contain matter—merely because space is geometrically capable of containing matter? None of these questions have yet been answered, nor is it probable that science will be able to answer them for a long time. They remain the domain of the philosopher.

The next problem is to discover the manner in which matter first entered the universe, and the manner in which it may possibly leave the universe—for matter appears to be not a necessary or permanent part of the universe, but a temporary accident—that is, there is no reason to assume that matter may not be able to enter space and then leave it again after a period of time, a period of great length in human or even in astronomical terms, but somewhat shorter than eternity. No solution has yet appeared to this problem, but it is not impossible that quasars may be the first step in the evolution of matter that has just entered the universe, and that pulsars or neutron stars may be matter on the verge of leaving it.

Every night it is possible to observe other phenomena related to the evolution of stars. How are stars born? How are galaxies formed? How do planets originate? And how will all these bodies evolve? In this regard, it must be remembered that the problem of evolution involves not only an explanation of the origins of existing things, but an indication of what will happen to them in the future.

THE EVOLUTION OF STELLAR SYSTEMS

The analysis of the evolution of star systems has greatly aided the development of a theory of stellar evolution. By studying the pattern of the evolution of a stellar system, it is possible to ascertain the stage of evolution of the component stars. The study of stellar clusters provides a good example. It has been established through observation that the stars of a cluster must have been formed at the very time that the cluster itself took shape; that is, a cluster is not the result of the gathering of pre-existing stars. There are two types of cluster: the globular cluster, shown by its pattern to be some billions of years old; and the open or galactic cluster, shown by its pattern to be young—in astronomical terms (tens or hundreds of millions of years old). The stars of globular clusters are seen to be small, red, dim, and of low mass, whereas the stars of open clusters have the opposite characteristics. The stars of the two categories are well separated in the spectrum luminosity diagram (the Hertzsprung-Russell diagram), and it can be concluded that an evolution has taken place from the first spectral classes to the advanced spectral classes. Thus the Hertzsprung-Russell diagram aids in the study of stellar evolution.

The correctness of proceeding in this manner may then be confirmed by studying other types of stellar systems: galaxies, for example. In a color photograph, the fringes of a galaxy appear bluish, whereas the center appears reddish. The stars near the edge are of the type referred to, in the preceding discussion of clusters, as young; those in the center are of the type characterized as old—confirming the validity of the observations made of the stellar clusters. Other considerations point in the same direction. Where young stars appear in a galaxy, clouds of gas are also observed, leading to the theory that the stars originated from the gas.

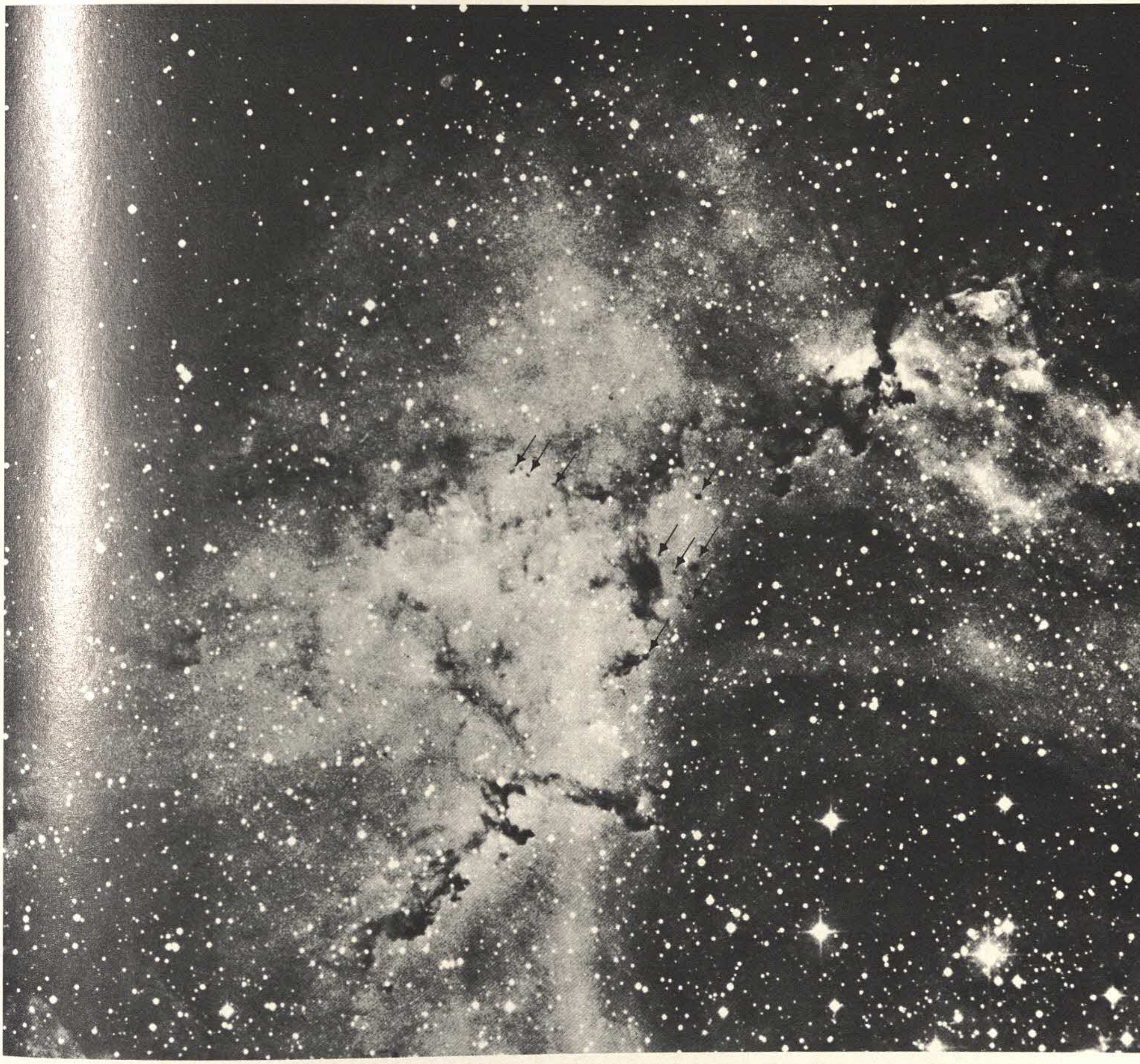
THE EVIDENCE OF THE NOVAS

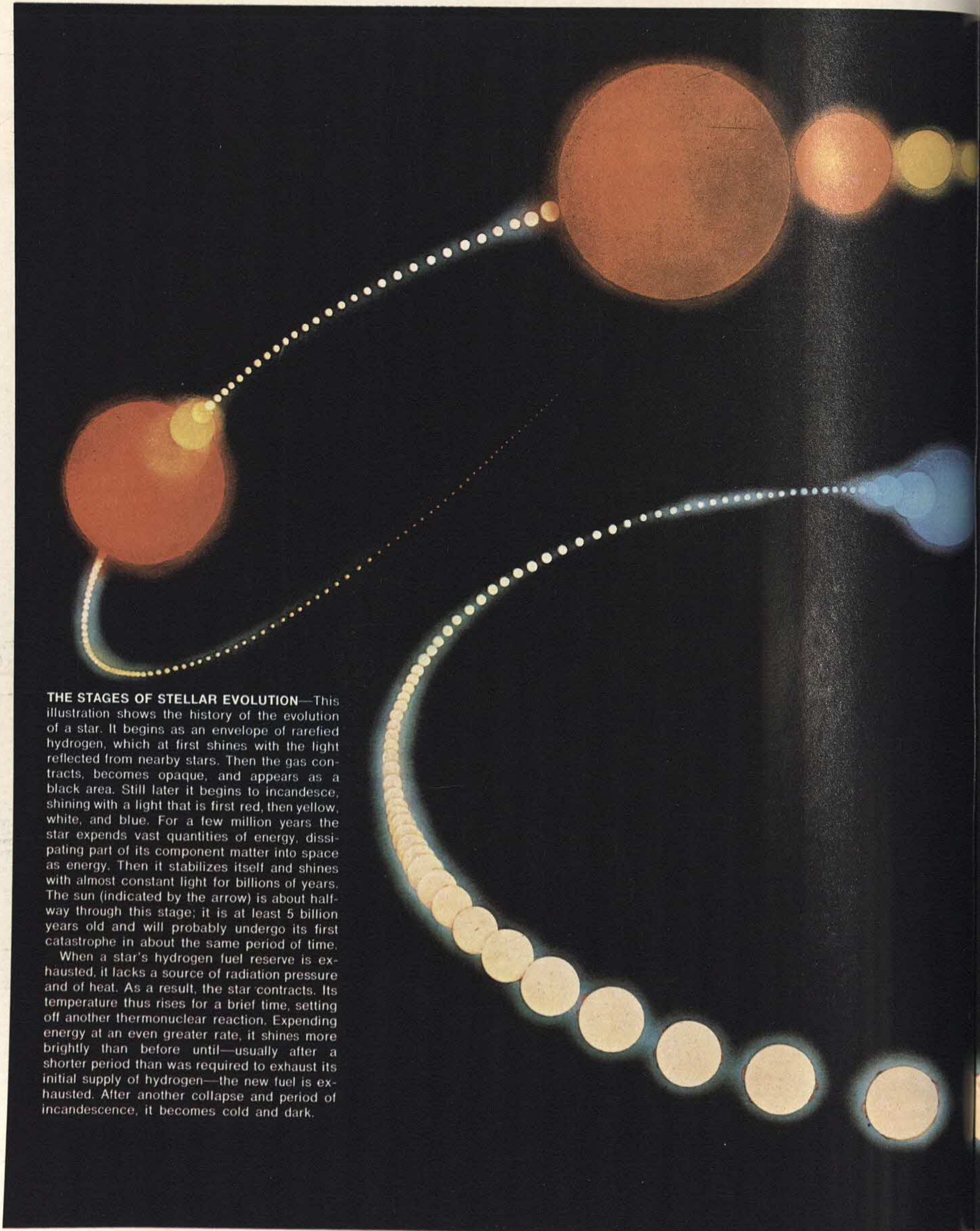
Another important phenomenon observed by astronomers is the explosion of novas and supernovas, stars that erupt catastrophically or completely destroy themselves. When these phenomena are measured statistically, it is concluded that they are likely to occur sometime to all massive stars. A star produces light by releasing energy from a reserve of thermonuclear fuel in its core. Little chance exists that this reserve can be exchanged with the material of the external atmosphere of the star; consequently, after the energy has been released over a period of millions of years, the star must contract. The compression that results, however temporary, raises the temperature at the core of the star, triggering another thermonuclear reaction using another type of fuel—heavier elements rather than hydrogen. The star then expands again, releasing more energy and becoming more luminous than before. It eventually recovers equilibrium and remains in this condition until the new supply of fuel is exhausted; at this point another eruption occurs, and the star again explodes as a nova. Finally, when the reserve of fuel is completely exhausted, the star develops into a cold celestial body—a phenomenon marking the end of its existence as a star.

The rate of evolution of a star depends on its mass. In the sun, the effects are only slightly manifest; they could not have been found if observers had not been looking for them. A star of twice the sun's mass burns its energy at such a rate that it cannot last more than about 3 billion years, whereas a star of 10 times the sun's mass has a lifetime measured in tens of millions of years.

As the composition of the star's interior becomes seriously modified, the star begins to move away from the main sequence, slowly at first. When about 10 percent of the star's mass has been converted to helium, the structure of the star changes drastically. The core becomes inert; all the hydrogen has been burned out, and the central region is composed almost entirely of helium with admixtures of heavier elements. The energy production now takes place in a thin shell where hydrogen is consumed and added to the inert core. The outer portion of the star expands outward; and as the star swells up, it may gradually rise in luminosity. The final stage of a star is a sphere not much larger than the Earth but with a density of 50 thousand times that of water; possibly the star is covered by a thin layer of ice and surrounded by an atmosphere of hydrogen and helium a few feet thick. The course of evolution differs for stars of the two population types.

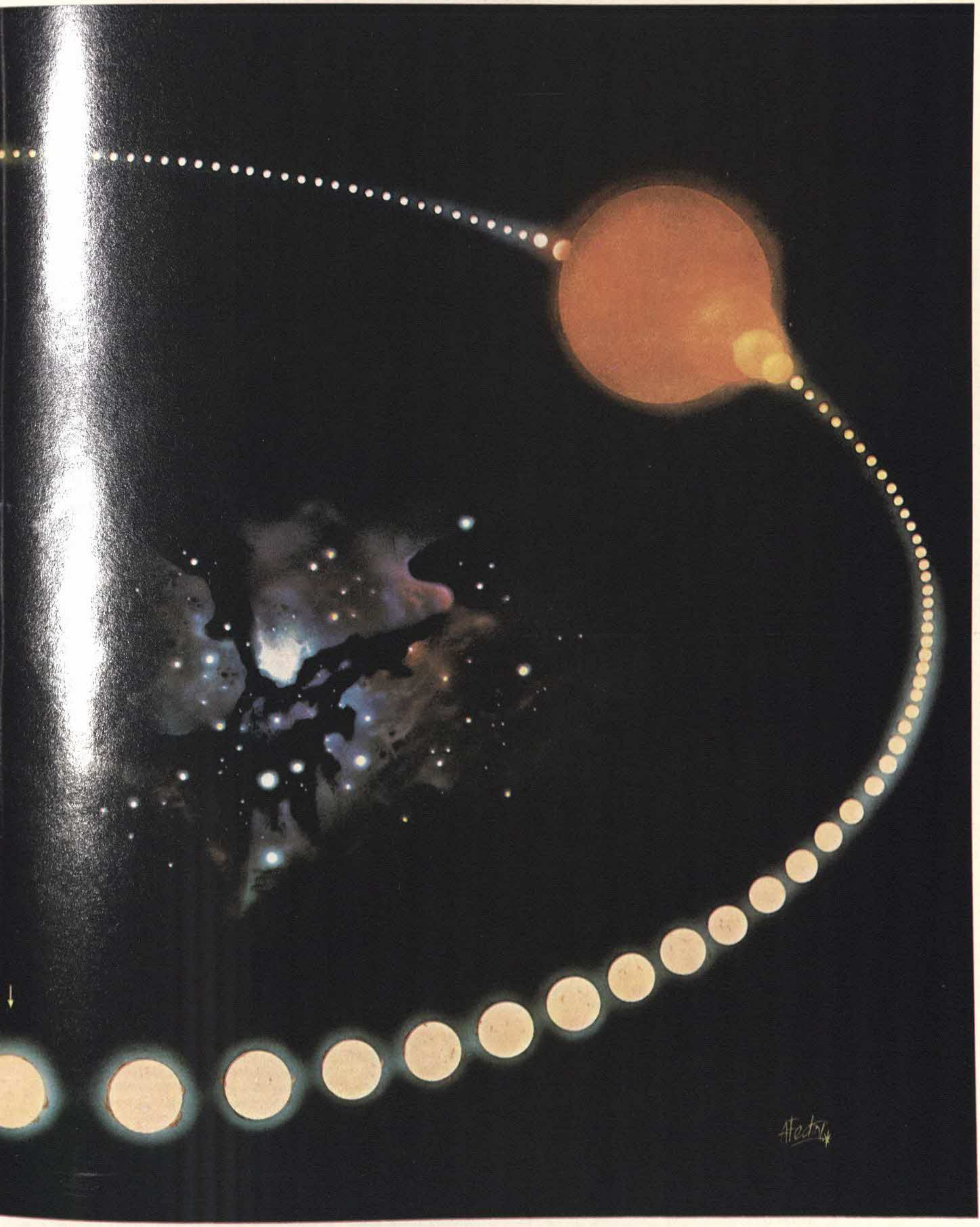
THE ORIGIN OF STARS—This photograph, of a gaseous nebula in the constellation Monoceros, shows how stars have their origin. The small black patches (indicated by arrows) are concentrations of highly condensed gas. Here the thermonuclear reaction that will transform the gas into stars has not yet taken place. However, some of these gaseous areas may eventually become incandescent.





THE STAGES OF STELLAR EVOLUTION—This illustration shows the history of the evolution of a star. It begins as an envelope of rarefied hydrogen, which at first shines with the light reflected from nearby stars. Then the gas contracts, becomes opaque, and appears as a black area. Still later it begins to incandesce, shining with a light that is first red, then yellow, white, and blue. For a few million years the star expends vast quantities of energy, dissipating part of its component matter into space as energy. Then it stabilizes itself and shines with almost constant light for billions of years. The sun (indicated by the arrow) is about halfway through this stage; it is at least 5 billion years old and will probably undergo its first catastrophe in about the same period of time.

When a star's hydrogen fuel reserve is exhausted, it lacks a source of radiation pressure and of heat. As a result, the star contracts. Its temperature thus rises for a brief time, setting off another thermonuclear reaction. Expending energy at an even greater rate, it shines more brightly than before until—usually after a shorter period than was required to exhaust its initial supply of hydrogen—the new fuel is exhausted. After another collapse and period of incandescence, it becomes cold and dark.



NOVAS AND SUPERNOVAS

stellar catastrophes

The explosion of a star is one of the most spectacular phenomena in the universe. As seen from the Earth, such an explosion appears as a sudden increase in the luminosity of a star. Sometimes, in fact, a star never previously observed or photographed suddenly becomes visible by exploding into a nova. This phenomenon is of great interest to astronomers; it was an exploding star, for example, that suggested to Hipparchus that changes could occur in the skies, and that precise charts of the skies would be required to determine and record their appearance in order to make comparisons when such changes occurred.

Stars that explode and so tremendously increase their luminosity are called *novas*, from the Latin word for "new." The term is, of course, a misnomer, because nothing about the star is new except the degree of luminosity that makes the star become easily visible for the first time to observers on Earth.

Observations of the increase in luminosity of novas, and measurements of the

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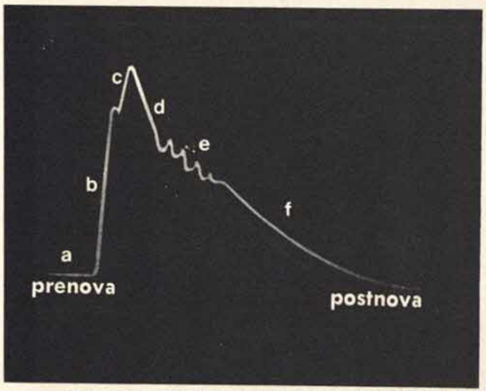

THE LIGHT CURVE OF A NOVA EXPLOSION—In this graph of the fluctuations of magnitude of a nova during its active period, the first part, representing what may be called the prenova phase, is flat **a** and corresponds to the relatively constant luminosity of the star before the explosion. This phase is followed immediately by rapidly increasing and uninterrupted luminosity **b,** corresponding to the brief period—usually two to five days—of the explosion.

The exact magnitude of the star before the explosion cannot be determined unless the nova can be identified with a previously observed star in a precisely defined position. Inasmuch as a nova is discovered only after its luminosity has increased significantly, usually enough to make the star visible to the naked eye (otherwise it is not likely to be even observed), the first stages of the explosion cannot intentionally be observed and, what is more important, cannot intentionally be photographed. The usual increase in luminosity is about nine magnitudes, in other words, the star becomes about 4,000 times as bright as it had been.

Before the star reaches its final phase of increasing luminosity, the increase is sometimes interrupted or even reversed briefly. This is followed by a final phase **c,** less rapid than the initial phase, during which the luminosity increases by about another two magnitudes. The next phase is that of an initial decline in luminosity **d** of about 3.5 magnitudes, amounting to a diminution of the maximum luminosity by about 25 to 30 times. This is followed by a transition phase **e,** which may have one of three different sets of characteristics: Some novas continually decrease in luminosity with no fluctuation; others decrease rapidly in luminosity and then become more luminous once more before finally declining; and still others continue to fluctuate in brightness indefinitely. The last phase of the graph, representing the postnova phase of the star, represents the final decline to a state of constant luminosity **f;** in this phase the star remains somewhat brighter than before the explosion.

Astronomers are greatly at a disadvantage because the prenova spectrum of the star is not usually available; if it were available, it might reveal many of the factors that brought about the explosion.

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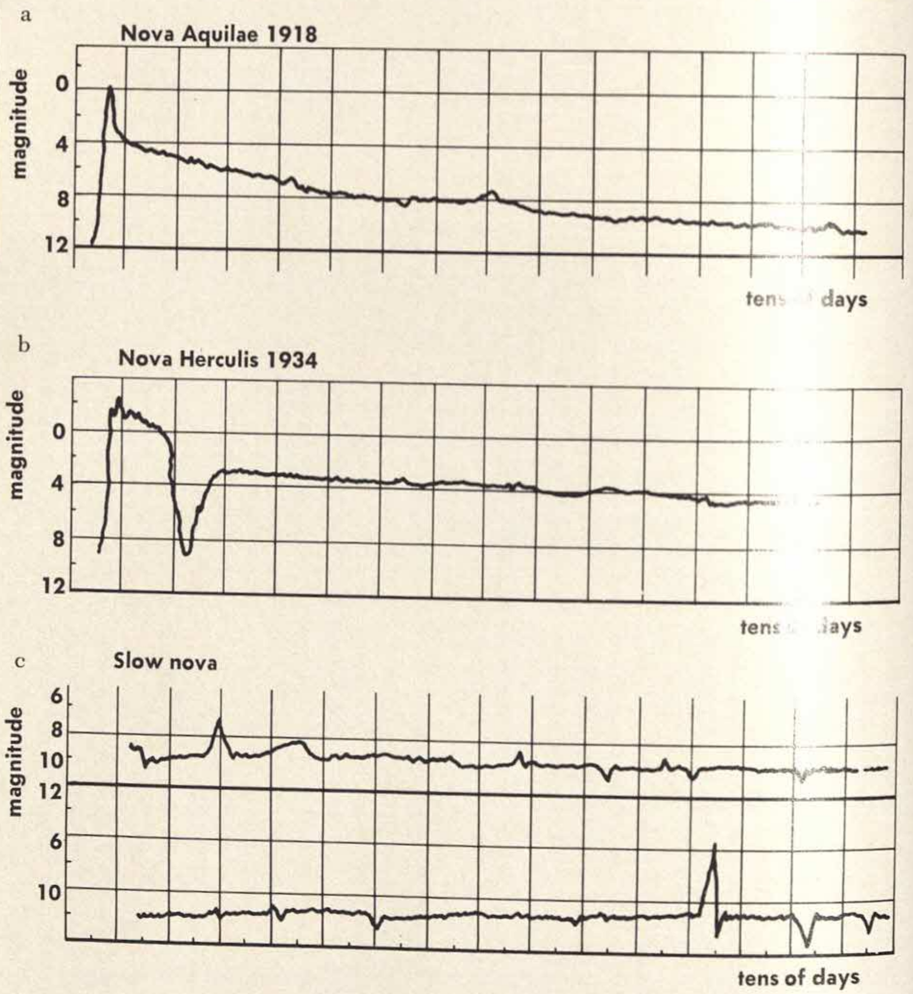


LIGHT CURVES OF NOVAS—These three graphs represent the light curves of novas. A nova is designated by the name of the constellation in which it appears, preceded by the word Nova and followed by the year of its appearance. When two or more novas appear in the same year, Roman numerals are used to distinguish them in the order of appearance. The curve of Nova Aquilae 1918 (Illustration 2a) shows an extremely rapid increase in luminosity, an undulating decline through the transition phase, and a postnova phase substantially brighter than the prenova phase. Inasmuch as the star had not been observed before the explosion, the magnitude at the beginning of the curve is unknown; but it may be assumed that a star in that position would have been observed if it were bright enough, that is, above a magnitude corresponding to the level of visibility made possible by the instruments of that period. Thus, although the exact magnitude of the star before it exploded cannot be known, its minimum initial magnitude can be set. Because sky atlases made in recent years locate rather dim stars with great precision, novas can sometimes be identified with such stars, but at an earlier time only the brightest stars could be so identified.

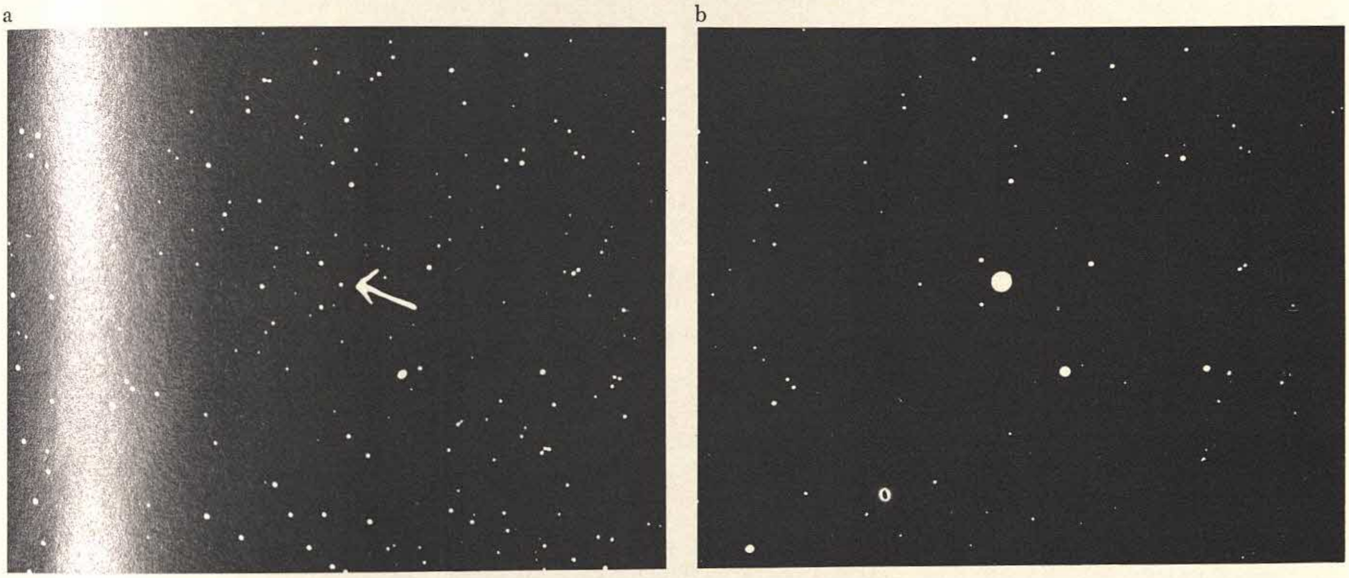
Illustration 2b is the graph for Nova Herculis 1934, which declined in luminosity rapidly in the transition phase, then recovered once more before the final phase of decreasing luminosity.

Illustration 2c shows a third type, different from the two preceding, the so-called slow nova. Its fluctuations are irregular as the first critical explosion is followed by others at intervals of a few years. No really clear distinction can be made between novas and certain types of irregularly variable stars, which may owe their variability to other causes.

absolute magnitude of these stars before and after an explosion, provide the basis for classifying such stars into two categories, novas and supernovas. In the first category are stars that increase their luminosity by about 10,000 times; those in the second category increase their luminosity even more. The two categories actually represent two distinct phenomena. The nova may be a normal stage in the evolution of massive stars. The phenomenon of the supernova, on the other hand, is more complex and less understood. When these stars explode, they eject an enormous quantity of matter; in some cases the remaining matter may form a neutron star.

3

AN IDENTIFIED NOVA—Very seldom can a nova be identified with a star; identification occurs only with the brightest novas that were bright enough, even in their prenova phase, to correspond to an observed star. Nova Aquilae 1918 was one such, identified in these photographs before and after the explosion. However, even when such an identification is possible, it does not provide a spectrum of the prenova star, which would give information necessary for the interpretation of the phenomenon.



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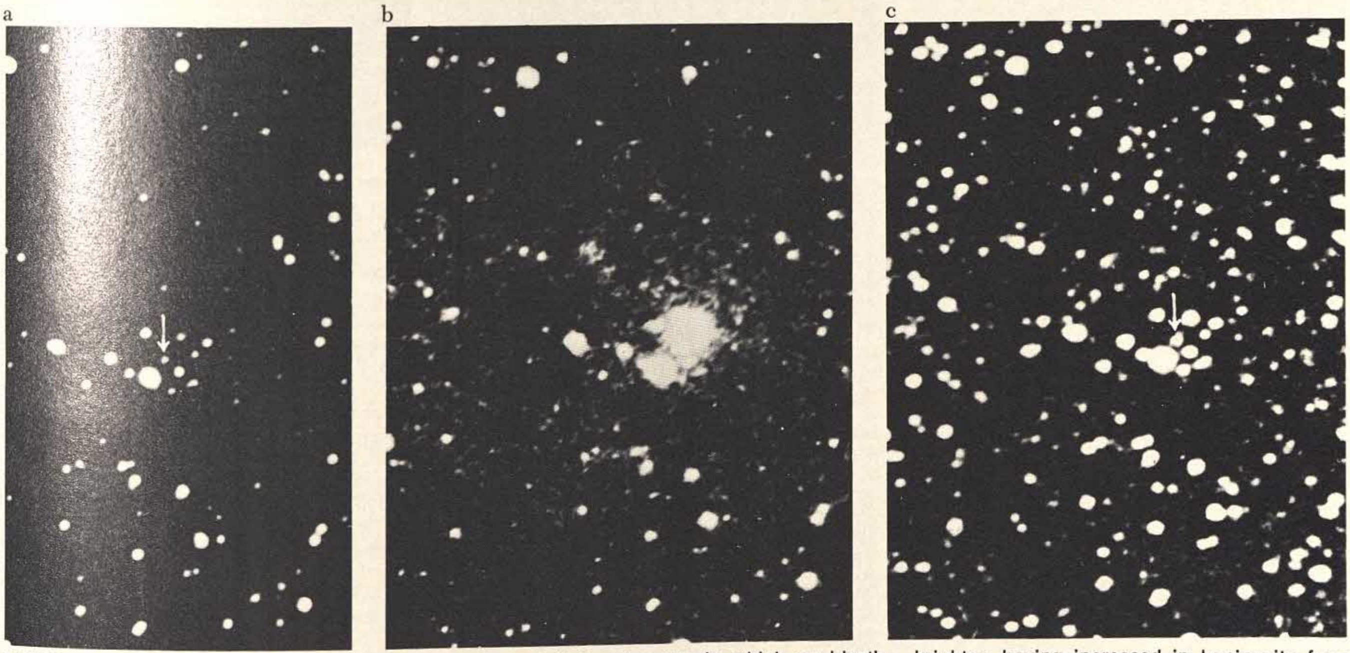

ANOTHER IDENTIFICATION—These three photographs were taken with a photographic telescope equipped with a 10-in. objective on August 7, 1907 (Illustration 4a); December 13, 1910 (Illustration 4b); and September 29, 1911 (Illustration 4c). They all show a region of the constellation Lacerta in which an identifiable nova appeared; it is indicated by an arrow in the 1907 photograph on the left and in the 1911 photograph on the right. In the first photograph, the star appears as a rather dim body; in the second, it is considerably brighter, having increased in luminosity from the 13th to the 5th magnitude; in the third, although still brighter than in the prenova stage, it has dimmed to the 11th magnitude. After a few years, the brightness of the nova remnant usually becomes steady again.

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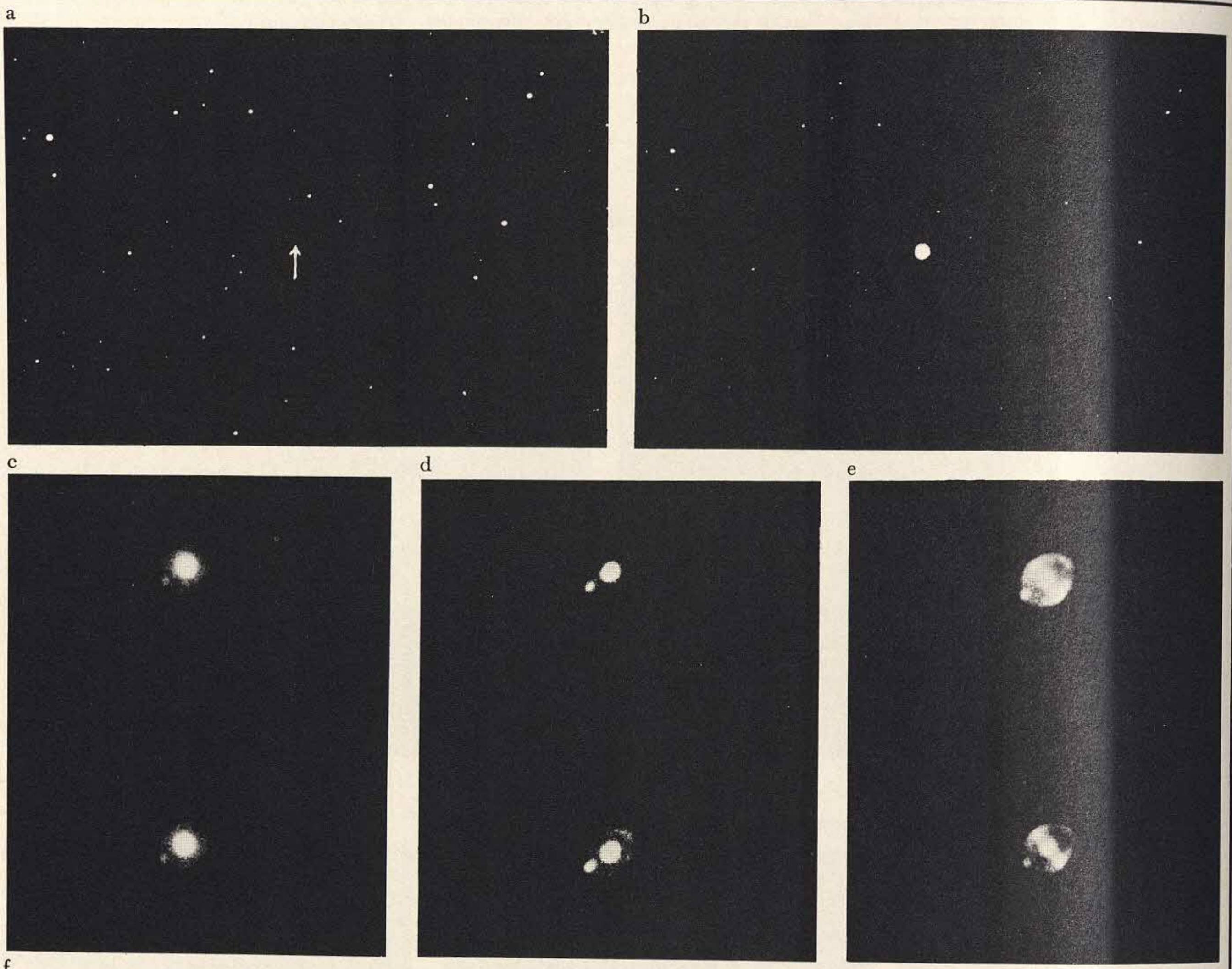

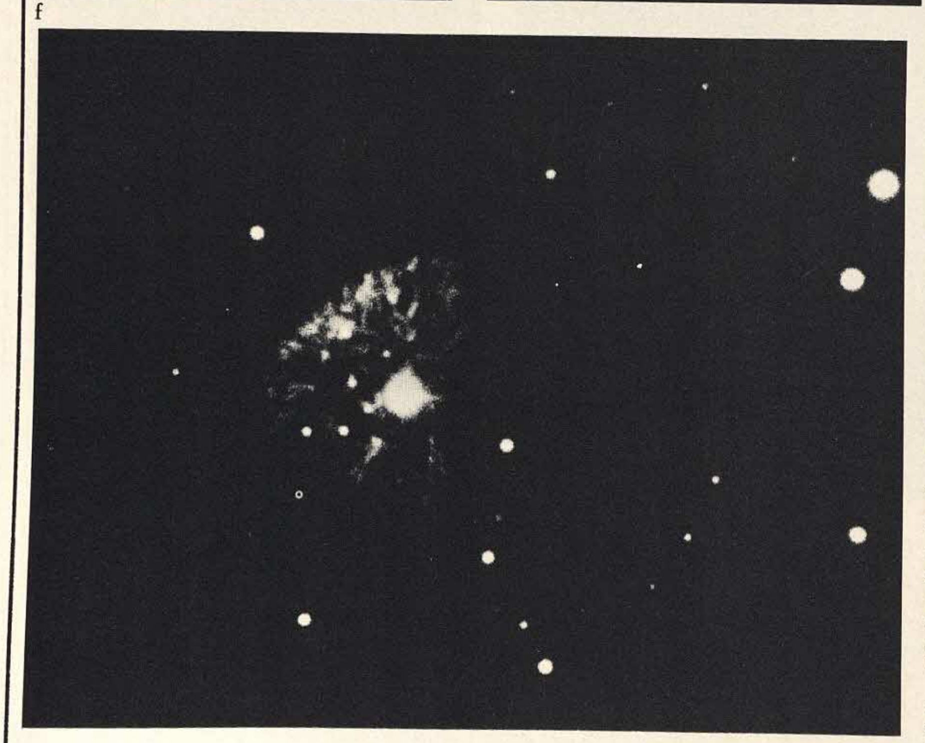

SHELLS BLASTED INTO SPACE—The explosion of a nova releases enormous energy, as is shown by the fact that it emits many thousand times as much light as the star in its prenova phase. This energy, produced in such a brief period of time, is enough to cause a great expansion of the external shells of the star's atmosphere. The five photographs above show the explosion of Nova Herculis 1934.

Illustration 5a shows the star before the explosion. Illustration 5b shows the star after the explosion and somewhat after it had passed its period of greatest luminosity.

The star, after 17 years, seems to be surrounded by a halo that appears differently in three photographs (Illustrations 5c, 5d, and 5e) taken with filters of different colors. The luminous ring that surrounds the star, giving it a resemblance to a planetary nebula, is composed of gases ejected from the star itself; as the distance is known, the velocity of the escaping gas can be calculated by actual observation; this velocity is the same as that measured by the spectroscope as the star was increasing in luminosity—between 100 and 1,000 km (about 62 to 620 mi) per second. The mass of the ejected gases, however, is only a small fraction of the mass of the star, and the star has resumed its stability.

Illustration 5f shows Nova Persei 1901, one of the more recent novas, photographed 50 years after it exploded.

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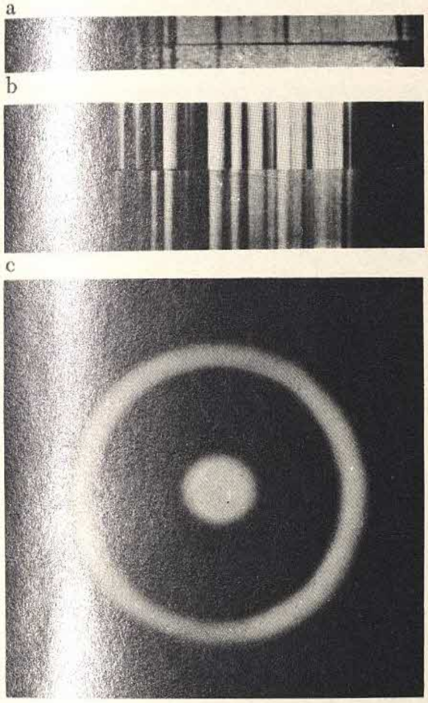

THE SPECTRA OF NOVAS—The spectrum of a nova in the first phase of the explosion is quite similar to that of a star in the prenova phase—a normal stellar spectrum with absorption lines. The two spectra shown in Illustration 6a, of Nova Aquilae 1918 and Nova Cygni 1920, are of this kind. Subsequently, emission lines appear in the spectrum (Illustration 6b), indicating that the explosion has fundamentally altered the effective temperature of the outermost part of the star.

The lines are noticeably broadened because of phenomena illustrated in Illustration 6c, which shows how an ordinary nova might appear from closer up, a few days after the explosion. The stellar body would be surrounded by an expanding gaseous envelope that emits the light associated with the spectrum of the star. As soon as the star begins to increase in luminosity, the lines of the spectrum show a strong Doppler effect, shifting toward the violet. This effect is an indication of the radial velocity of approach as the star expands and its outermost surface comes closer to the Earth.

ONCE EACH 350 YEARS—Astronomers' statistics show that a supernova appears in each galaxy beyond the Milky Way on an average of about once every 350 years. Illustration 7 shows before-and-after pictures of the extragalactic spiral NGC 5457, Messier 101, in which a supernova exploded on February 7, 1951. Its absolute luminosity is about one ten-thousandth of the luminosity of the entire galaxy, which contains 100 billion stars; therefore, the luminosity of this supernova alone is equivalent to that of 10 million stars combined.

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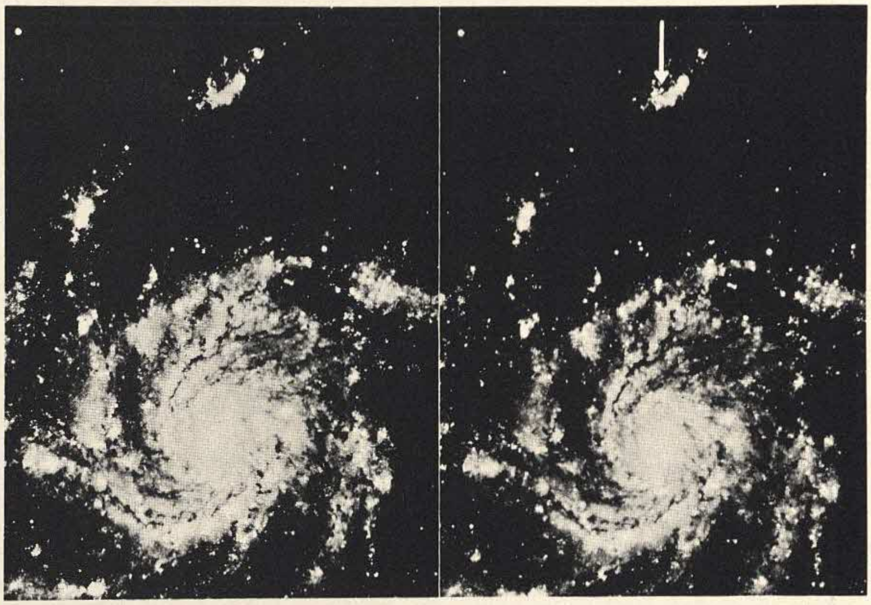

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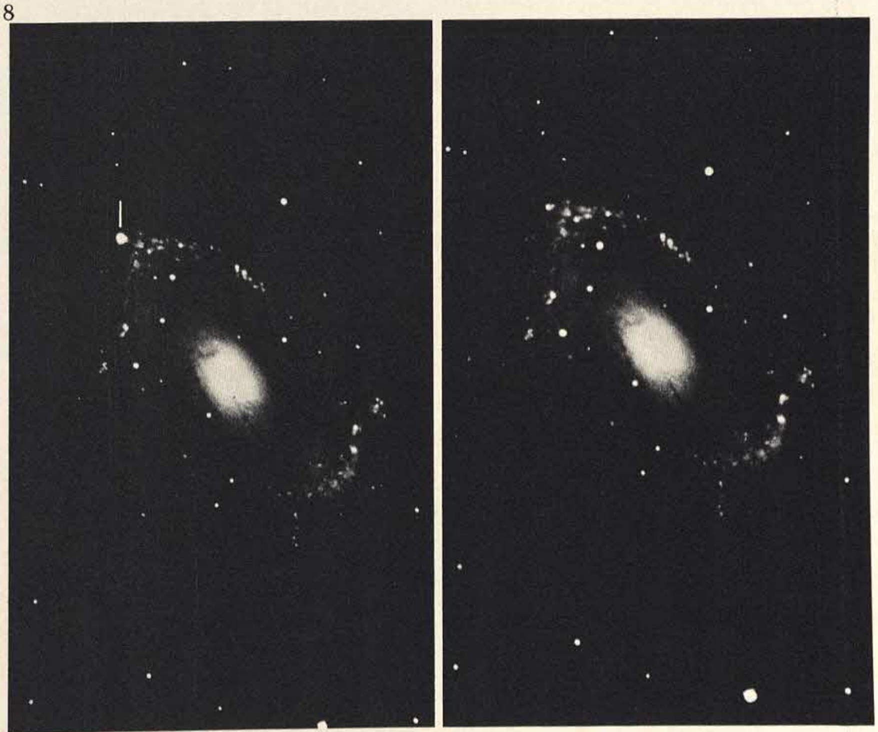
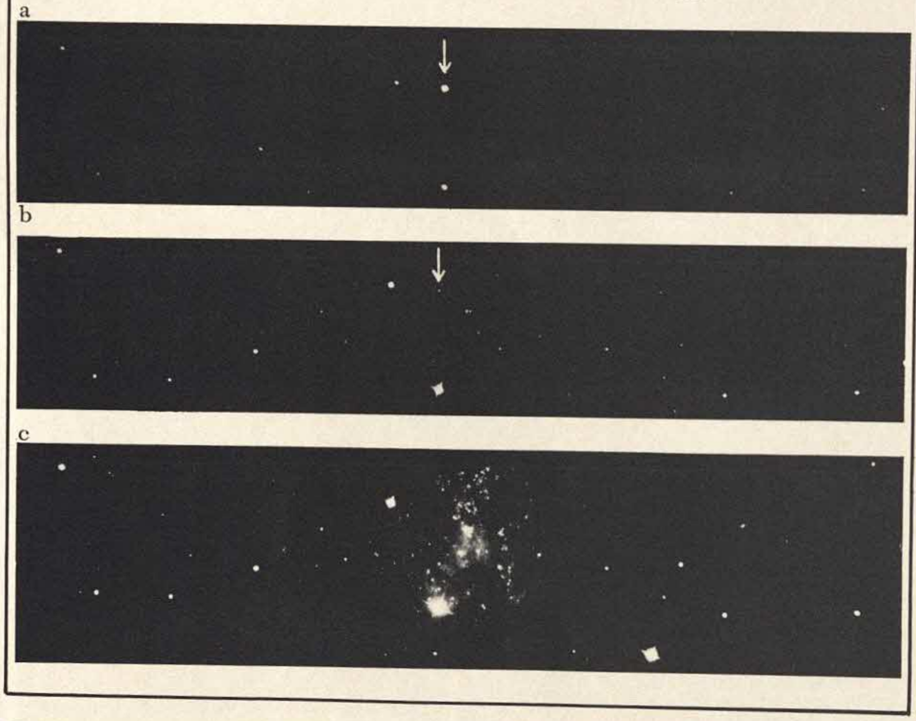


SUPERNOVAS—Although supernovas are rare phenomena, their exceptional brilliance makes them visible at very great distances. Inasmuch as there are millions of galaxies within the range in which supernovas can be photographed, it is not especially difficult to find a supernova. This supernova, which appeared on May 10, 1940, in the galaxy NGC 4725 in the constellation Coma Berenices, had disappeared less than a year later.

Although novas with apparent magnitudes brighter than the 1st magnitude have not been recorded recently, the supernova observed by Tycho Brahe in 1572 (Tycho's Nova) attained a brightness equal to that of the full moon, visible even in daytime and, some said, even through clouds.

9

THE MAGNITUDE OF A CATASTROPHE—This series of three photographs of the explosion of a supernova accurately indicates the magnitude of the catastrophe. The first photograph (Illustration 9a), taken with the very short exposure of 20 minutes, shows only a few stars; the brightest is the supernova that appeared on August 23, 1937, in the galaxy IC 4182. By November 24, 1938, the star had diminished considerably in brightness; this photograph (Illustration 9b) required an exposure of 45 minutes. The third photograph (9c), taken on January 19, 1942, with an exposure increased to 85 minutes, shows the entire galaxy, but there is no trace of the supernova; yet the maximum luminosity of this star equaled the brightness of a billion normal stars combined.



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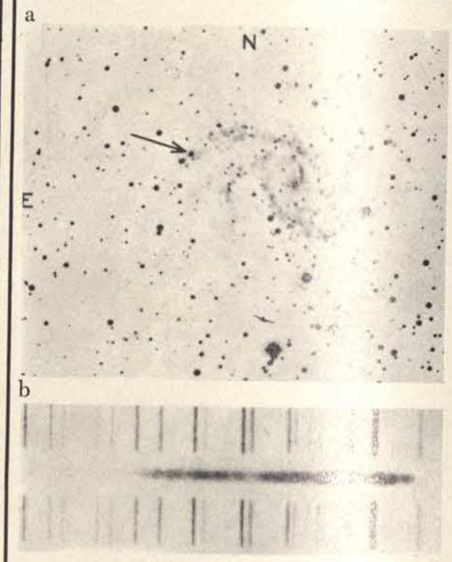
THE SPECTRUM OF AN EXPLODING STAR—A supernova exploded in the extragalactic spiral NGC 6946 on July 10, 1939. Although it was one of the brightest of its kind, it was not especially noticeable from the Earth because of its great distance. Below, beneath the photograph (Illustration 10a) of the galaxy showing the star, are two spectra (Illustration 10b) that were recorded during the critical phase of the explosion. They show how, during the brief time that elapsed between the two photographs of the spectra, the absorption lines narrowed.



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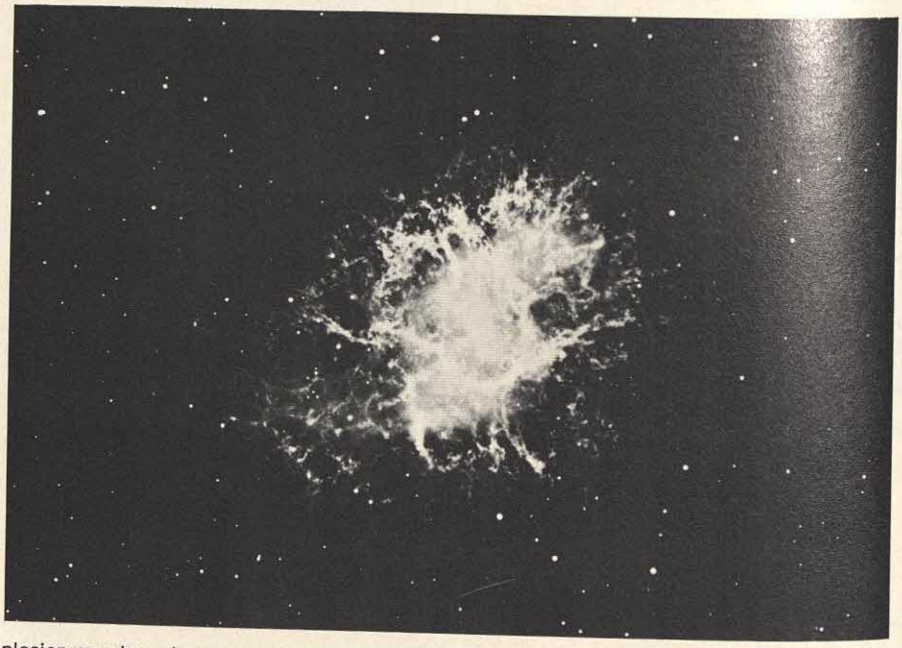
THE RESULTS OF THE CATASTROPHE—The explosion of a supernova causes the emission of a quantity of matter, amounting to a considerable portion of the total mass of the star. This matter is shot out into space, as in the case of an ordinary nova, with such speed that it escapes from the star and continues to disperse. The result, shown in this photograph of a supernova that exploded in the constellation of Taurus around 1054, is the formation of a vast nebula (the Crab Nebula).

This phenomenon was described previously, but the photograph shows the filament structure especially clearly. At the center of the nebula, presenting a very special composition, is the star that probably survived the explosion. It emits light and radio waves with variations as short as tenths of a second and is believed to be a rotating neutron star. The nebula emits polarized light, x-rays, and intensely strong radio waves, and has a magnetic field. It is also agitated by perturbations that spread within it with a velocity close to that of light.

No one has yet completely and satisfactorily explained the phenomenon of the explosions of novas and supernovas. Two distinct possible causes have been suggested: A sudden increase in energy may have been triggered by a thermonuclear reaction; or—in a somewhat more complicated hypothesis—the explosion may have been preceded by a marked contraction of the star, affecting the mass even after the explosion, but with rather different results.



QUASARS | a hundred billion stars in one

The Earth's own Galaxy, the Milky Way, is estimated to contain a hundred billion stars, swirling in a vast disk with a diameter of 100,000 light-years. From a position slightly within the edge of this disk, astronomers on Earth look out into the universe beyond and see other such galaxies as far as their instruments will allow. Occasionally, they encounter phenomena that challenge man's knowledge of the universe about him.

Within the past 10 years, numerous objects have been located that appear smaller than any galaxy, yet emit more energy than all the stars of the Milky Way together. These objects were first discovered through their strong radio emission. Because they resemble stars, they

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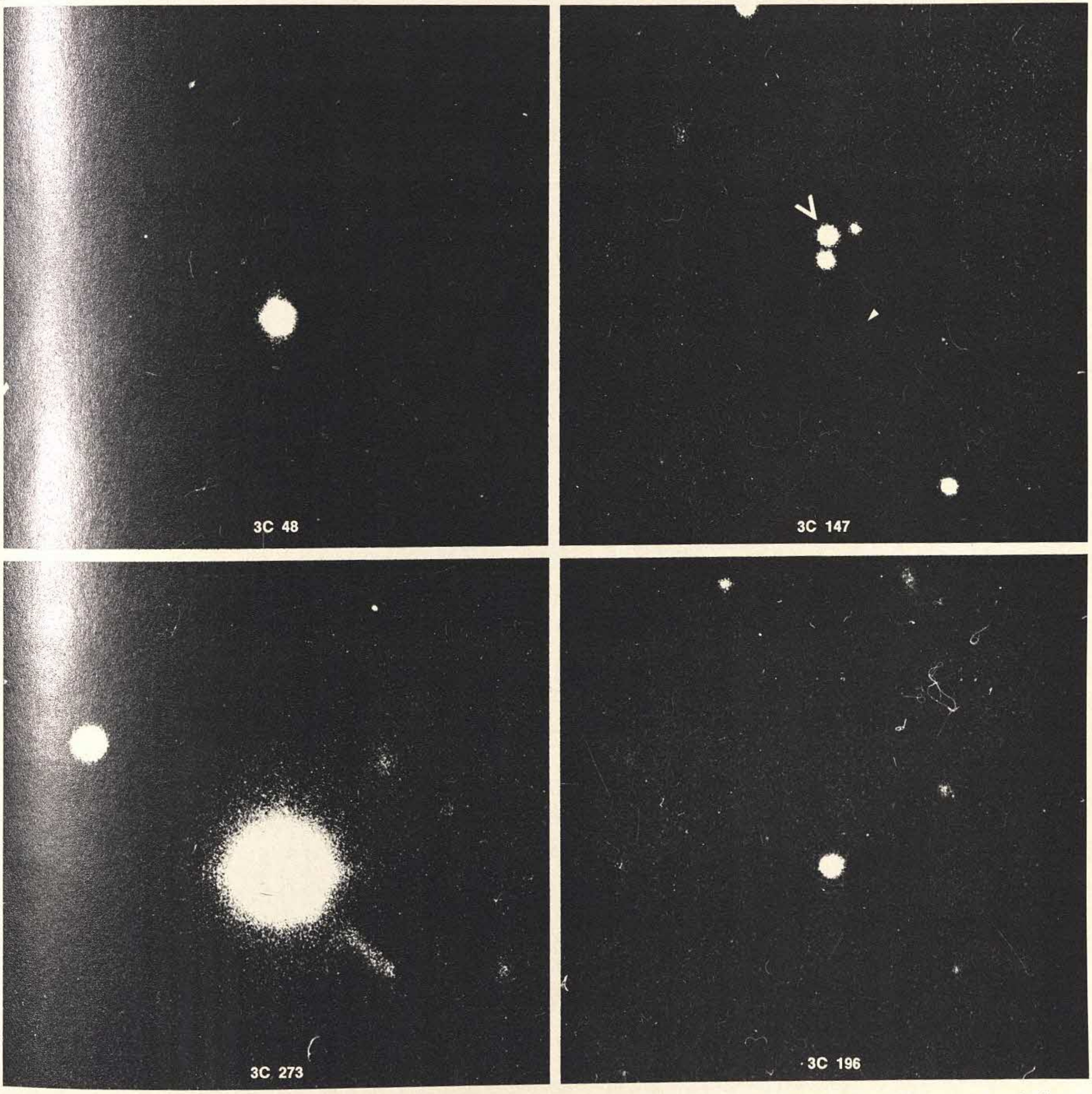


QUASARS—These photographs illustrate the optical identification of quasi-stellar radio sources.

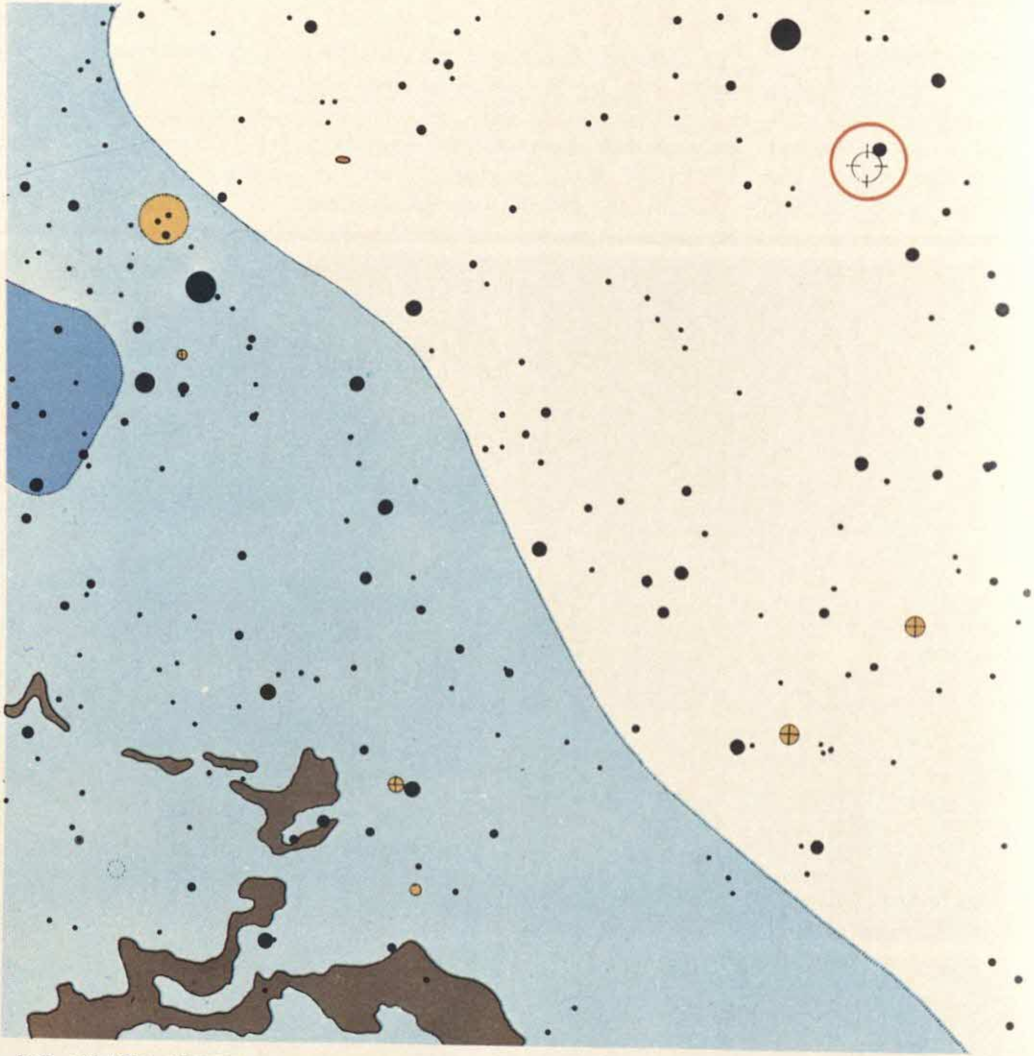
Common to all such sources is a starlike image. The number printed under each image is from the Cambridge catalog (hence the C), a catalog of celestial objects which produce continuous radio emission spectra.

3C 48 (upper left) was the first starlike (discrete) radio source discovered. It had been observed as an emitter of radio waves and was then pinpointed as the blue star shown in the photograph.

3C 273 (lower left) is the brightest quasar yet discovered, shining with the brightness of 200 galaxies from a distance of 1,500 light-years. The diagonal streak to the lower right of the quasar itself is a tongue of luminous material 150,000 light-years long, known to astronomers as component A, or 3C 273A. Component B—the round light source—is actually extremely small visually (smaller than 0.01 second of arc); it appears much larger in the photograph because of the scintillation and halation resulting from the long exposure required to render component A visible.

Spectroscopic analysis has shown that quasars exhibit a strong Doppler shift toward the red. If quasars obey the same velocity law as galaxies, their Doppler shift implies that their distances are extragalactic and the greatest of any known objects.

2



RADIO SOURCES AND OPTICAL IDENTIFICATION—This map of the celestial sphere contains a radio source (indicated within the red circle). Two types of radio sources exist: extended sources, which emanate radio waves from large areas; and discrete sources with dimensions that are small or unmeasurable by the resolving power of the radio telescope. Once a radio source has been discovered, the immediate task is to identify the optical source that is the site of emission of the radio waves. Such identification can sometimes be made by searches of celestial maps. In most cases, the photographic maps made by the Mount Palomar Observatory are used. The search is carried out by observing, on the photographic negative, all those celestial objects that may have some exceptional feature in their structure. When the radio source cannot be found on a celestial map, a search must be undertaken using an extremely large telescope.

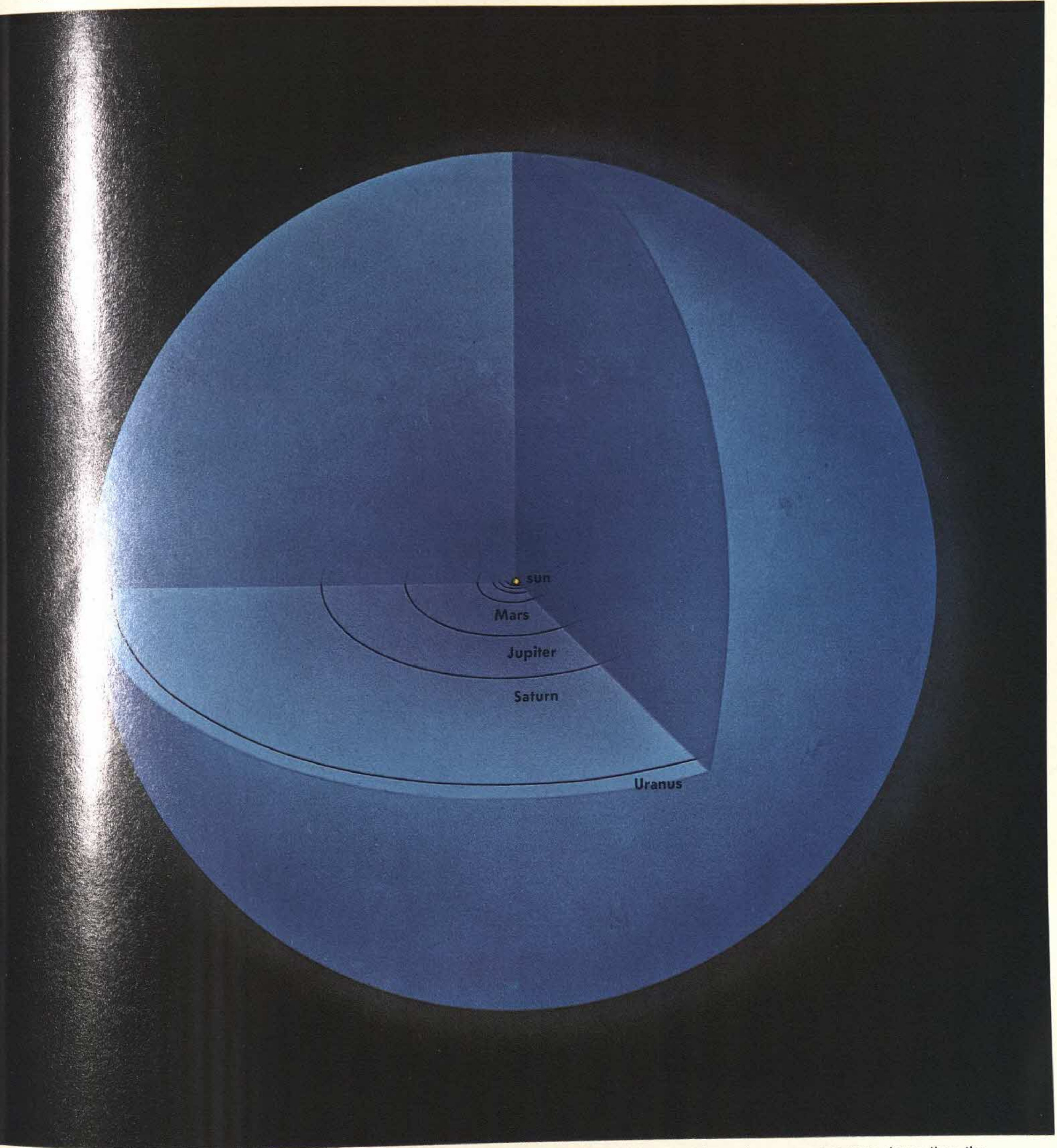
were called quasi-stellar radio sources or QSR's. Later, when similar optical objects that were radio-quiet were discovered, the name "quasi-stellar objects" (QSO's) was assigned. The name "quasar" originally referred to the radio sources, the QSR's. This name has been strongly resisted by the astronomical community and was only recently accepted to refer to both QSR's and QSO's as a group.

THE DISCOVERY OF QUASARS

Quasars were discovered through radio astronomy. The pioneer of this technique, the American radio engineer Karl Jansky, first discovered radio waves coming from the Milky Way with a radio telescope built in 1931. The radio energy he observed did not come from stars, but from fast-moving electrons in interstellar space.

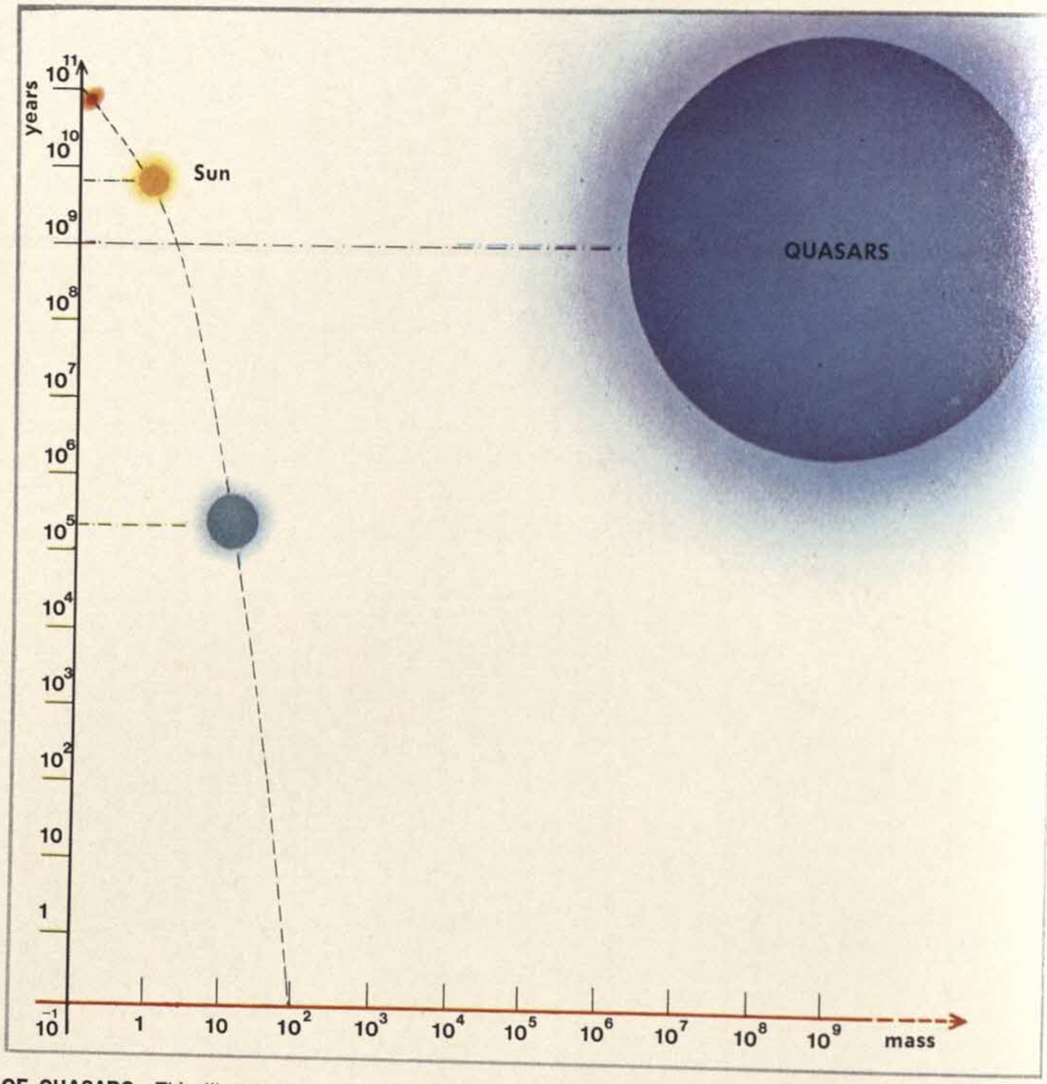
Early radio surveys showed that there were also radio emissions from localized areas. Maps were developed to show the lines of radio emissions, somewhat as topographical maps show the contours of the Earth's surface; on the maps, all points of equal radio emission intensity were joined. The maps showed the two types of sources: extended sources (weak surface intensities emanating from large areas); and discrete sources (extremely intense emissions from small areas).

The discovery of radio emissions from a discrete source naturally stimulates the curiosity of an astronomer. One of his first concerns is to determine if an optically visible object corresponds with the radio source. It was not difficult to identify most of the areas and objects showing up on the radio emission maps. Many of the extended sources corresponded to visible nebulas and external galaxies. Some discrete sources, however, did not easily identify with previously observed optical objects. In 1960, however, one of these radio sources was identified with a starlike object having unusual spectral features. In 1963, following an accurate determination of the position of another of these sources by the lunar occultation technique, a second starlike or quasi-stellar radio source was identified. In the spectrum of the object, familiar lines of hydrogen were found. It was also found that the wavelengths of the visible light



THE DIMENSIONS OF QUASARS—The dimensions of a quasar can be determined once its mass, mean density, distance, and presumed surface brilliance are known. The distance can be deduced from the optical Doppler effect (the amount of red shift); the density and mass are estimated theoretically. The conclusions are that a quasar must have a diameter at least a thousand times greater than the sun, and that it could contain a large part of the solar system, as shown in this illustration. The density of a quasar is probably slightly higher, on the average, than that of water. If a quasar has a mass equal to about a billion times that of the sun, but a density almost equal to that of the sun, its diameter should then be about a thousand times greater. Bearing in mind that the internal regions of a quasar are more dense than the outer regions, the diameter of a quasar turns out to be about equal to that of the solar system. With the same mean density as the sun, a quasar is thus an extremely massive body. Astronomers are still wondering how such celestial objects, so similar to stars but excluded from that category by the theory of stellar stability, can exist.

4



THE STABILITY OF QUASARS—This illustration shows (on the abscissa) the mass of a stellar body, and (on the ordinate) its average life. As is apparent from the graph, the average life depends on the mass: the greater the mass, the shorter the life-span.

Stars with a mass about ten times greater than that of the sun can exist in such a form no longer than a million years. After this they do not explode or die out, but their mass is reduced and they are transformed into stars with a smaller mass and a longer life. A star with a mass similar to that of the sun can exist for 10 billion years. With 1/10 of this mass its life-span would be hundreds of billions of years. If the curve were extrapolated to stars with masses equaling billions of solar masses, such stars could live for only a few seconds; in other words, they could not exist. However, this conclusion directly contradicts the observations made of quasars. To resolve this contradiction, astrophysicists have pointed out that it is still possible for a stellar sphere with the dimensions and the mass of a quasar to be stable, provided that its mass exceeds a hundred million solar masses and that it rotates slowly.

For a celestial object having these and certain other characteristics, astronomers can predict stability conditions and many other properties (which can lead to more effective observation) and then proceed to compare the observed characteristics with those predicted by theory.

It is predicted by theory and confirmed by observation that the surface of a quasar is extremely hot, at least as compared with the surfaces of stars. The surface temperatures of stars range, on an average, from something like 2,000 to 3,000° C for the so-called cold stars, to 6,000° C for the sun, to 15,000 to 20,000° C for the so-called hot stars. The observed electron temperatures for quasars are some tens of thousands of degrees.

were shifted toward the red end of the spectrum by 16 percent of their wavelength, an unheard-of amount. If these red shifts were Doppler, and if the QSR obeyed the Hubble velocity-distance law, these objects were immense distances—millions of light-years—away. This accounted for their weak photographic images; however, it did not account for the enormous intensity of their radiation.

From Earth, quasars are extremely faint dots of light. Rapid variations in this light imply that they are compact bodies. If the calculation of their distance is correct, however, they emit light and radio waves with an energy equal to that of hundreds of galaxies. Several mechanisms have been proposed to explain this energy. These include collisions of galaxies, supernovas in great quantity, annihilation of matter by antimatter, star collisions, and the release of gravitational energy. The theory currently in favor centers on the release of huge amounts of gravitational energy in an extremely massive object. Information is not yet adequate to decide the issue, and quasars remain a great astronomical puzzle.

THE STRUCTURE OF QUASARS

To explain quasars, astrophysicists have worked out a theory based on spheres of gas that could conceivably resemble a quasar. Although quasars are seen as single bodies at a great distance, it seems that they are bodies of exceptionally great mass—at least a billion times the mass of the sun. On this model, they are not agglomerations of stars, but, more probably, they are large gaseous spheres. The theoretical conditions of stability for such a gaseous sphere are beyond the classical laws of thermodynamics.

If the energy radiated by quasars is mainly gravitational, it could be derived from the release of energy as the various parts of the mass are brought closer together by their mutual attraction. In a sense, this is the same fórm of power obtained from water falling under the force of gravity and turning the turbines of a hydroelectric power station. There is a limit, however. The energy cannot escape (in the form of radiation) if the radius of the mass becomes smaller than $R = 2GM/c^2$. (R is the radius, M the mass, G the universal gravitational constant, and c the speed of light.) The energy emitted by a quasar thus indicates that its mass is millions or billions of times that of the sun. How these large masses behave in a highly condensed state is one of the major questions posed by the discovery of quasars.

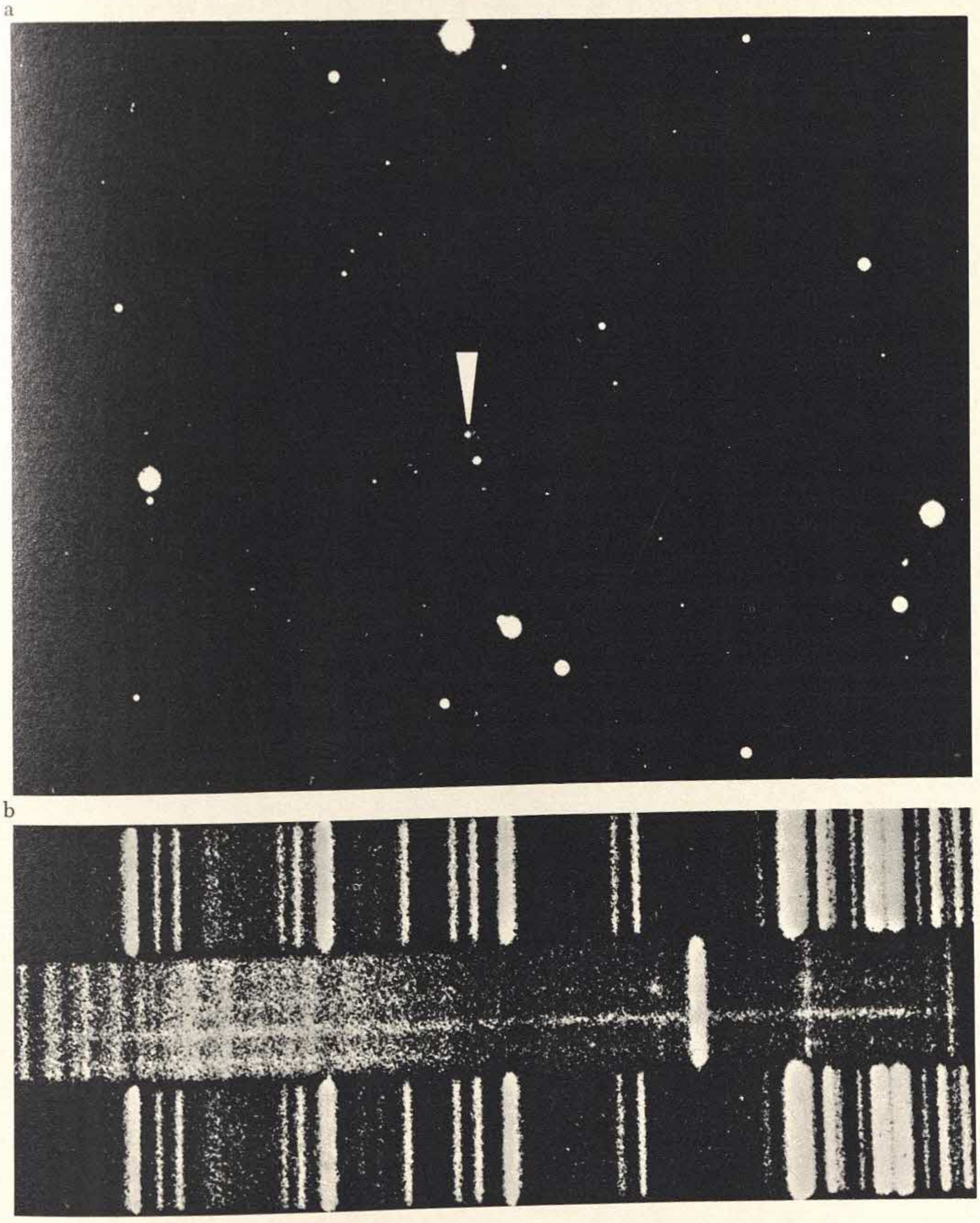
Much remains to be answered regarding the effects of enormous gravitation on radiation, the behavior of matter under extreme condensation, and the effects of a condensing mass composed of both matter and antimatter. Astronomers and astrophysicists throughout the world are addressing these problems with the resources of the largest and best-equipped observatories at their disposal. Certain measurements can be made only with the largest existing telescopes, and many major new telescopes were, therefore, under construction or being planned in the early 1970s. From this effort may come the first clear understanding of gravitation and, eventually, the unified field theory so long sought.

If, as astronomers believe, quasars are the most distant objects in the universe, they will also be extremely useful in the study of the geometry and history of the universe itself.

THE OPTICAL SPECTRUM AND ENERGY OF QUASARS—Illustration 5a shows the small sphere of a quasar (indicated by the arrow). In Illustration 5b the spectrum of the same quasar is shown in the center strip. Alongside it are the two spectra of iron used for comparison.

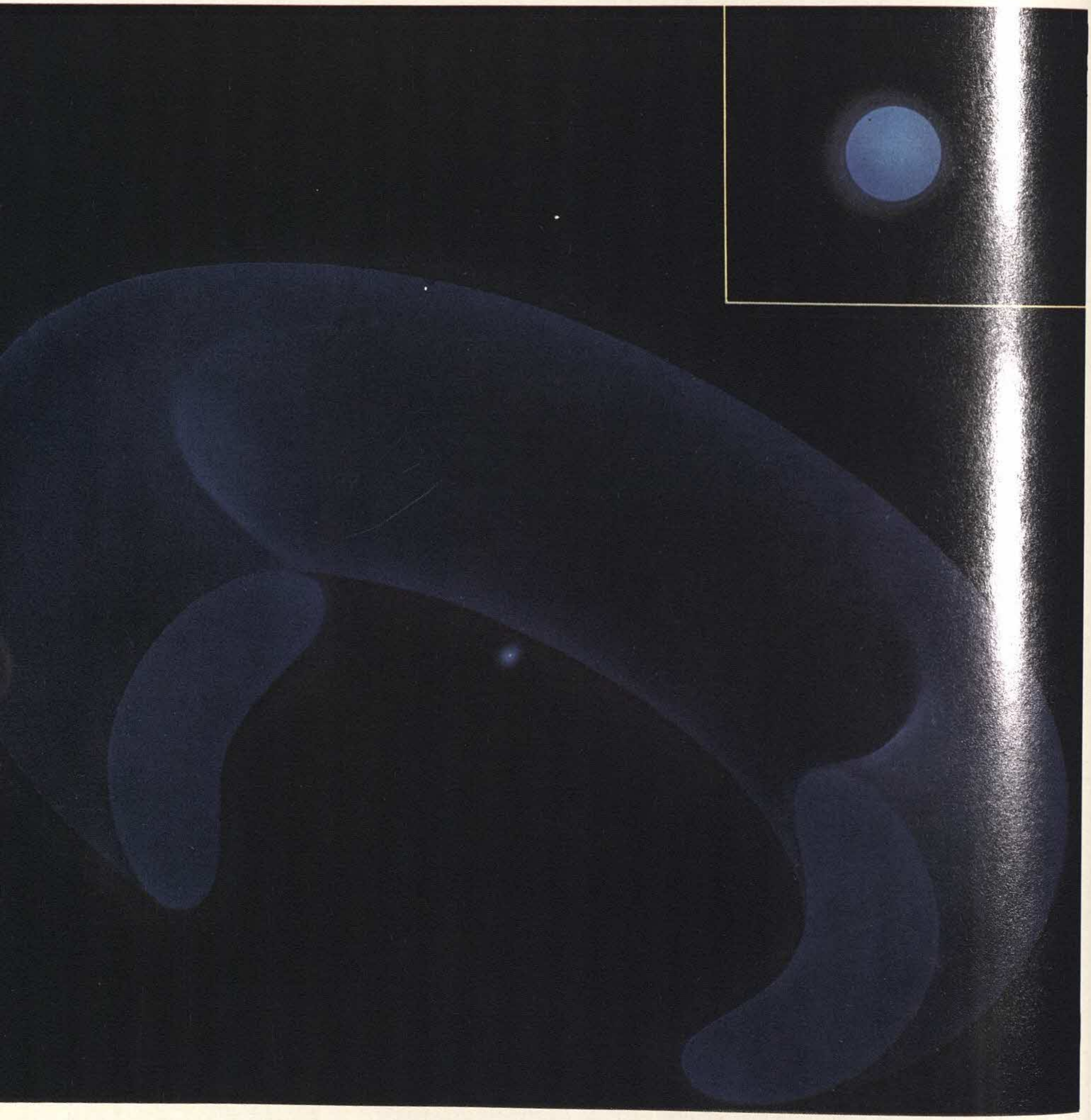
The shift of the lines indicates the extremely high velocity of the object. The nature of the lines indicates that quasars consist of normal material at high temperatures.

5



6

A VAST SOURCE OF RADIO EMISSION?—Astronomers have verified that, in most cases, quasars radiate from a wider area than that observed optically. (A celestial object a thousand times larger than the sun is visible only as a dot if viewed from a distance equal to that of the nearest quasar.) Unlike light emission, which radiates from a hot object, the radio emission is assumed to emanate from a band around the object itself. The large illustration below is one of many concepts; it represents the band in cross section, while the small square represents an enlarged image of the central body.



THE GALAXY | stars, dust, and gas

Among all the celestial objects that astronomers have observed since ancient times the system of stars that makes up the Milky Way—also called the Galaxy—is without doubt one of the largest and most important. On a clear moonless night it can be seen by anyone whose vision is not obscured by the glare of city lights. At any hour of the night—and on any night of the year—some part of the Milky Way is always visible in the sky, sometimes higher and sometimes lower over the horizon.

As a luminous streak, the Milky Way traverses the entire sky from one horizon to the other. If it were possible to observe the part hidden by the horizon, the Milky Way would be seen to form a complete, great circle on the celestial sphere. Its outlines are irregular, its width is not constant, and its luminosity changes from point to point. In some areas it seems to be split into two parallel streaks; but to an observer on Earth, it appears to encircle the entire range of view. The Earth's solar system is about midway between the hub and the rim.

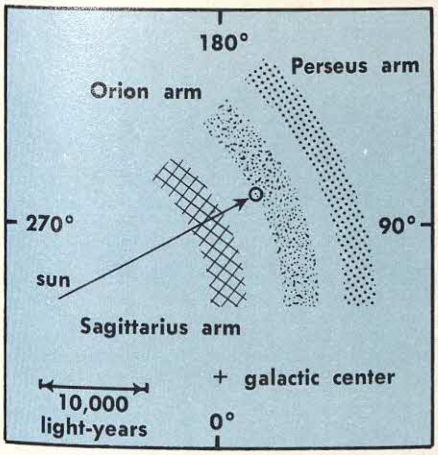
In ancient times it was believed that the Milky Way was placed in the realm of the fixed stars—that is, on the outermost celestial sphere where the stars are fixed like so many lanterns. Early observers were not interested in the nature of the Milky Way except in a fanciful way; Greek mythology held that it was a stream of milk emanating from Juno's breast as she fed Hercules.

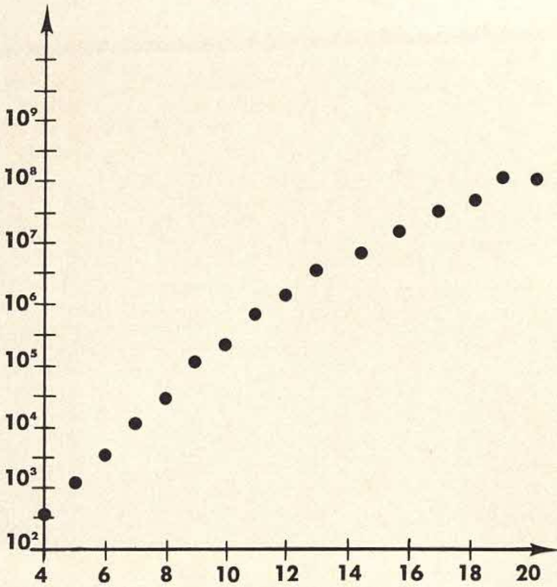
Later it was held that because divine power could not have created the whole celestial sphere of fixed stars as a single entity, it must have been created in at least two pieces and then joined together. The joining, being imperfect, was supposedly revealed by the irregularity and partial transparency of the Milky Way. Ancient civilizations imagined that behind the opaque vault of the fixed stars was the luminous empire or abode of the gods, and that this abode was luminous; therefore, should some point on the vault of the fixed stars be transparent, the light of the empyrean could pass through.

SPIRAL ARMS IN THE MILKY WAY—In other external galaxies that seem similar to the Milky Way, the brighter stars and nebulas are arranged in loose spiral patterns. It is natural then to search for similar features in the Milky Way and try to fix the position of the sun with respect to the spiral arms. In other galaxies these spiral patterns are very large-scale structures extending over thousands of light-years. These distances must be observable in the Milky Way if evidence of spiral arms is expected.

Since interstellar obscuration limits severely the distance that can be seen telescopically, astronomers eagerly turned to radio astronomy. Indeed, the radio observations of 21 cm interstellar hydrogen reveal an intriguing hydrogen distribution structure that resembles spiral arms. However, the results are open to considerable interpretation, mainly because the method of distance determination is very indirect, and because astronomers see the spiral structure in other galaxies at optical wavelengths not in the radio region.

Optical observations, even for the brightest objects, are limited to within a few thousand light-years of the sun. Furthermore, the corrections necessary for interstellar extinction and the uncertainties in the intrinsic brightness of the objects make the distance determinations rather uncertain. Nevertheless, if kinds of objects are selected that appear to define spiral structure in external galaxies (such as very young star clusters, supergiant stars, Cepheid variables, and clouds of ionized hydrogen gas), and if the distances to these same kinds of objects in the Milky Way are determined, a picture of segments of spiral arms emerges, as shown in this illustration. The arms are named for the constellation in which they appear most prominently. The sun lies near the inner edge of the Orion arm. The spacing of the arms is reasonably close to the spacing observed in other galaxies—and even though the picture is most incomplete, astronomers believe that the Galaxy has a well-developed spiral pattern resembling that of M51, the Whirlpool Nebula.



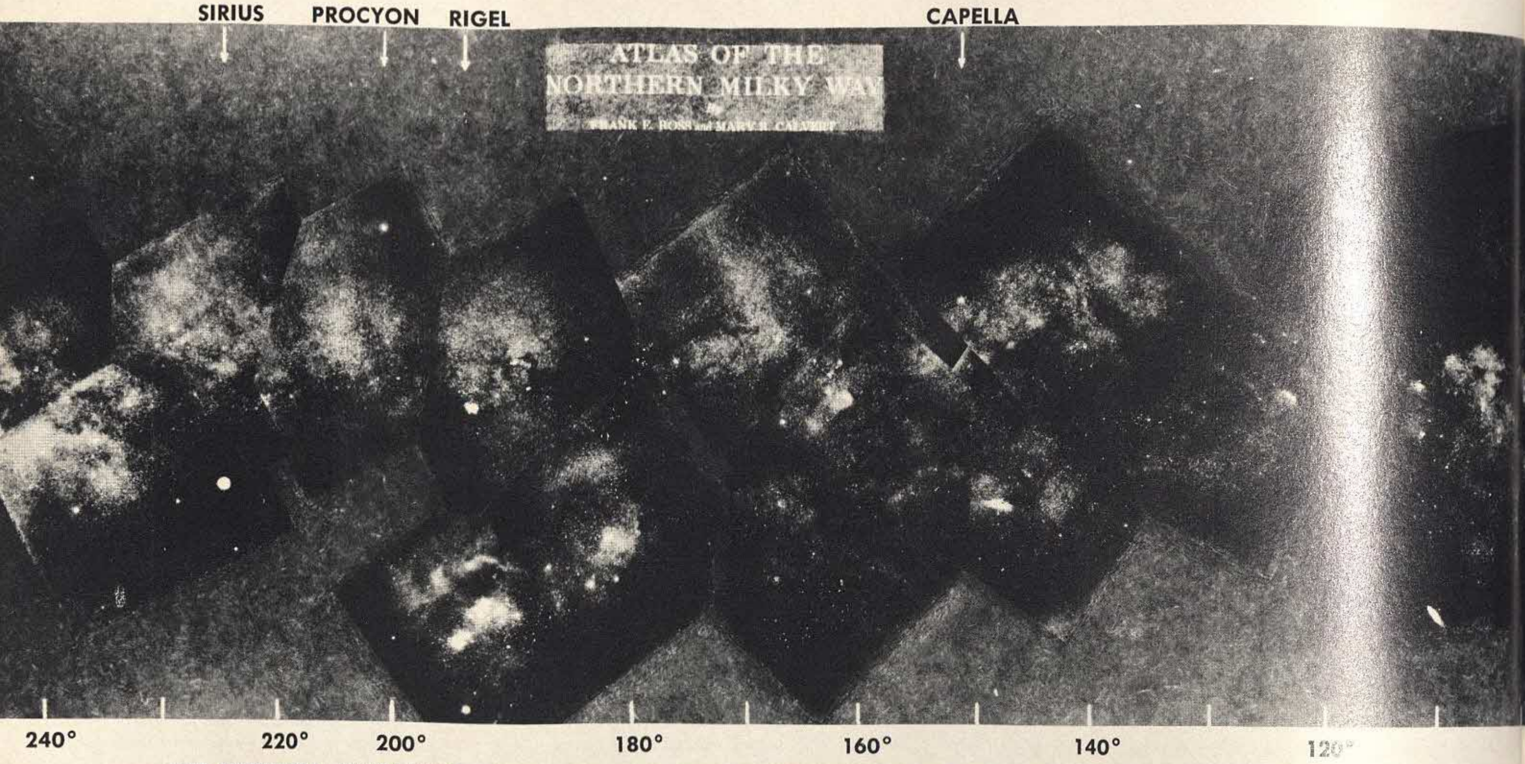


THE NUMBER-MAGNITUDE DIAGRAM—In this illustration, the stellar magnitudes appear on the abscissa. The number of stars of a given magnitude is shown on the ordinate. Because the range of numbers is very large the graph is logarithmic. The important point is that, even up to stars of the 20th magnitude, the curve continually increases, indicating an ever-increasing number of stars as magnitude increases. The curve eventually begins to level off, due to the effects of light absorption by interstellar dust. If continued, the curve would eventually reach a maximum and then decrease as the edge of the Galaxy is reached.

FROM GALILEO TO HERSCHEL

These fanciful speculations on the nature of the Milky Way came to an abrupt halt when Galileo first observed the Milky Way telescopically. He noted immediately that where the eye saw only a great mass of luminosity, the telescope showed numerous stars invisible to the naked eye and barely perceptible even through the telescope. In the regions where the stars were least numerous, the haze of the Milky Way was less luminous—but it was still possible to distinguish some stars. The weak stars were more numerous in these regions than in the background of the sky away from the Milky Way.

It appeared, then, that the Milky Way was made up of numerous, distant, faint stars, individually invisible to the naked



THE NORTHERN MILKY WAY—Using a mosaic of photographs from all parts of the Milky Way visible from the Northern Hemisphere, the American astronomers Frank Ross and Mary Calvert constructed a map of the northern Milky Way. Because of the latitude from which the photographs were taken, the map shows a little more than half the luminous ring. The numbers indicate the galactic longi-

eye but perceptible in their totality as a faint whitening. For almost another century no further progress was made. Meanwhile, telescopes were becoming more and more powerful, and exploration of extraterrestrial space had reached beyond the limits of the planetary system. In Galileo's time most studies were concerned chiefly with the disposition of celestial bodies. In the following period, when Newton's laws were applied to the study of the motion of celestial bodies, knowledge of the planetary system was deepened; knowledge of the stars, however, remained limited and confused.

Further progress was due to the work of the English astronomer William Herschel, who speculated correctly that the Milky Way was simply the combined appearance of an enormous number of stars located around the planetary system at tremendous distances; the form and boundaries of the Milky Way permitted the conclusion that the stellar system surrounding the planetary system was not without limits.

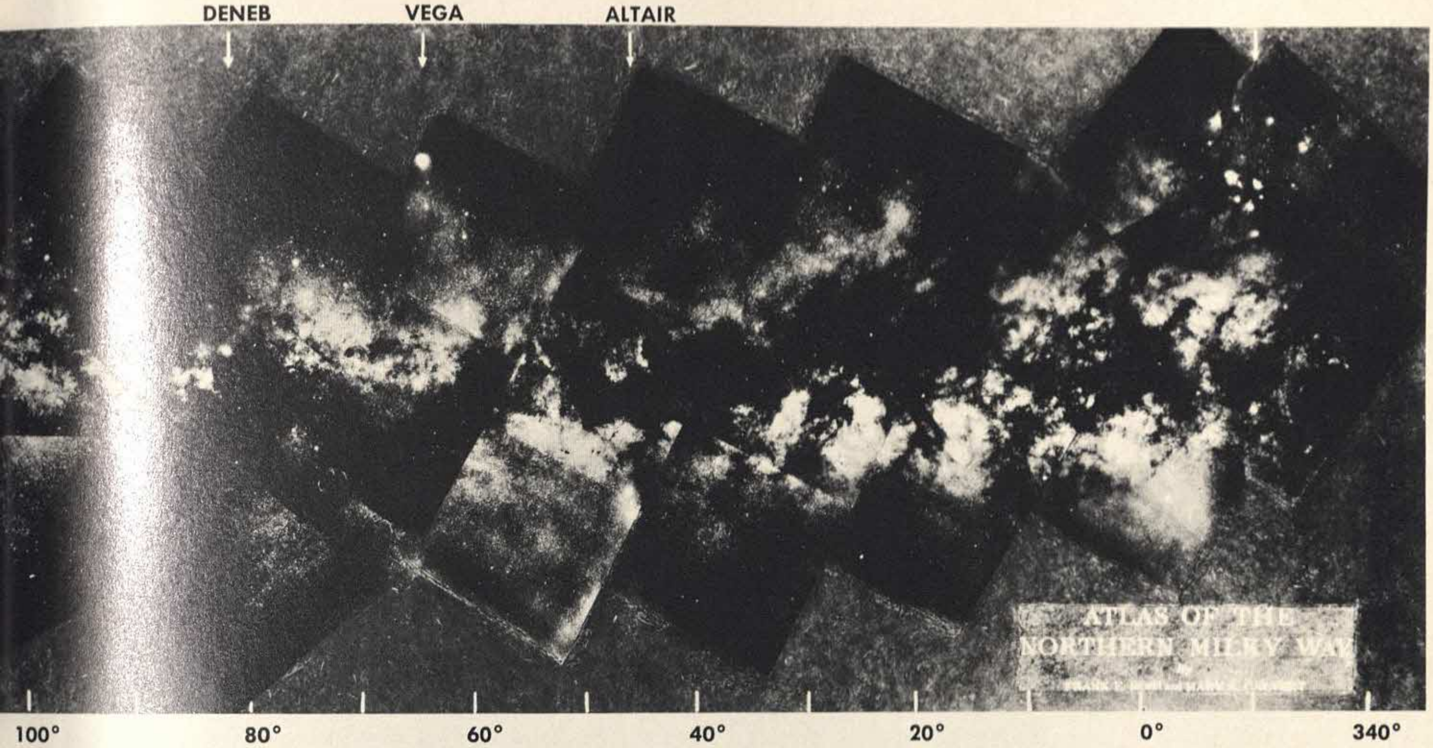
Because Herschel had powerful telescopes at his disposal, he was able to begin counting the stars that could be observed with the same instrument at the same magnification in every direction, working on the assumption that the extent of the stellar system represented by the Milky Way would appear to be greater where the stars were more numerous. This assumption, however, could not be verified because the presence of opaque, light-absorbing materials in the interstellar space made it impossible to observe all the stars, especially in certain directions. Nevertheless, Herschel's notion of the Milky Way, although partially mistaken, led to the construction of a fairly accurate celestial map that does not differ much from celestial maps in use today.

THE GALAXY

The studies following those by Herschel were largely confined to retracing his footsteps. After that, important progress was made. In attempting to classify all observable objects within the Galaxy it was noted that globular star clusters and open star clusters are located at various distances. Also observed were innumerable gaseous nebulas, as well as nebulas composed of fine dust. A way was found to measure the distances of these objects, and it was thus possible to construct a rough map of the Galaxy with some indications of its dimensions and boundaries.

It was then discovered that the globular star clusters were scattered throughout the Galaxy, so that a study of these clusters led to a better understanding of the Galaxy's limits. The possibility of determining the distances of extragalactic nebulas by means of the Cepheid variable stars brought out clearly the fact that the universe contains innumerable other stellar systems, some of which resemble the Milky Way. These distant stellar systems are also called galaxies.

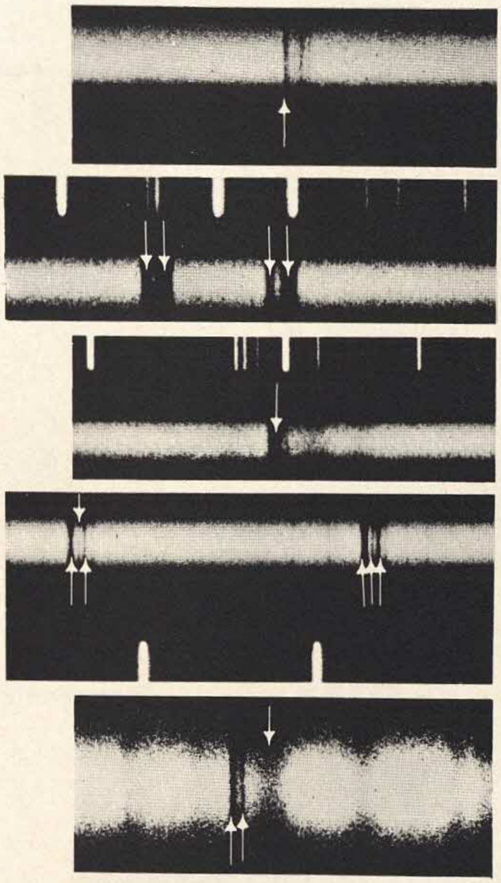
The greatest success of classical astronomy with respect to the Galaxy was in the study of its dynamics. The stars which form the Galaxy revolve around its center of mass in orbits that are always extremely large; some orbits—those of the external stars—are larger than the orbits of the internal stars. By very complex measures derived from a wide range of statistics, the periods of rotation of many of these stars around the galactic center have been determined. Stars located close to the sun have periods of about 200 million years. This knowledge makes it possible to estimate the mass of the part of the Galaxy interior to the sun. The period of rotation depends on two quantities: the diameter or the major axis of the orbit, and the gravitational mass. The period and the diameter are known for a large number of celestial bodies; this knowledge allows the derivation of other less precise but still significant properties, such as the magnitude of the galactic mass. It turns out to be about 400 billion times greater than the sun's mass. At least a third of this mass is interstellar

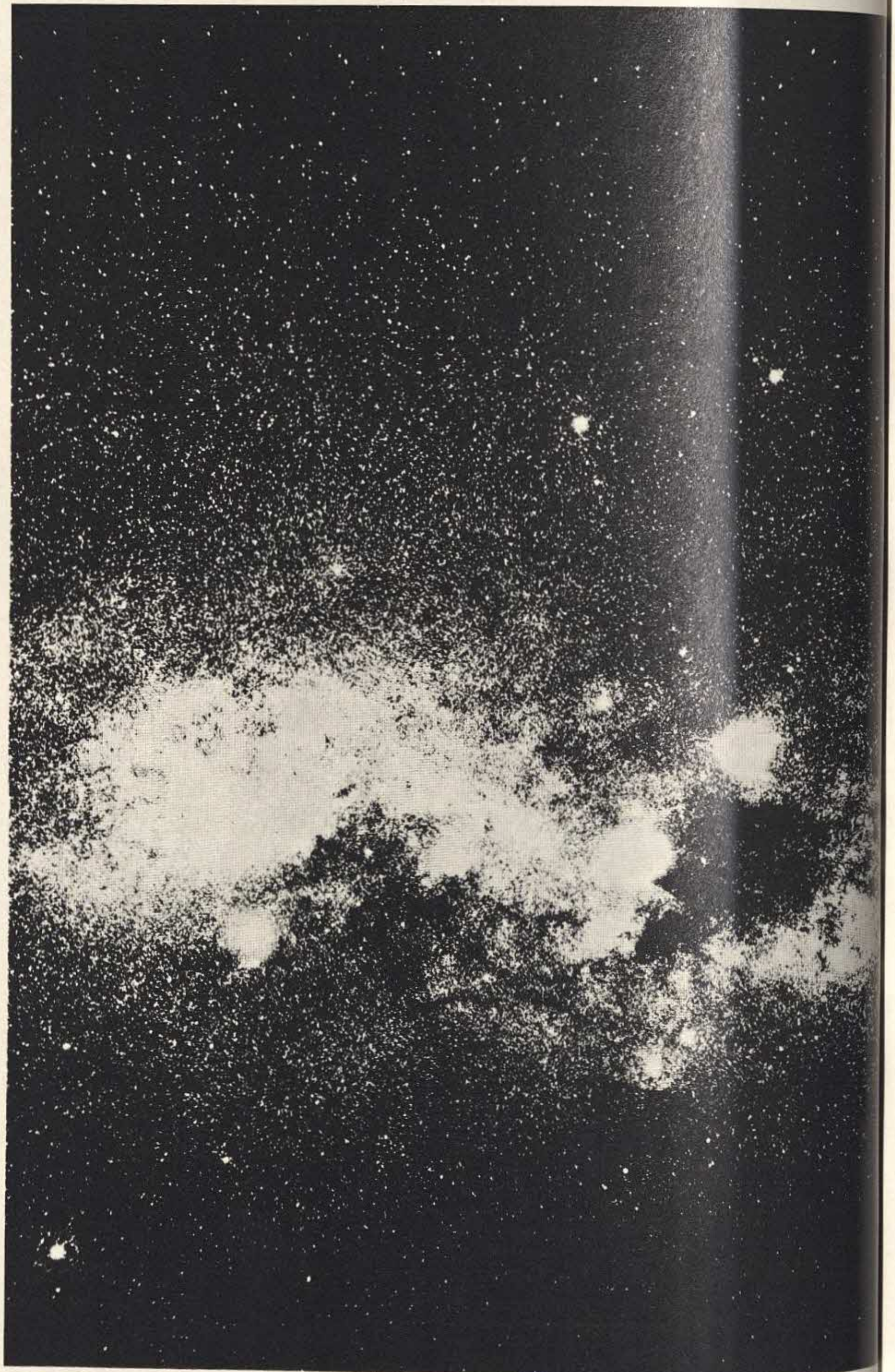


tudes in degrees while the arrows point to the positions of the more important stars. The most interesting characteristic in such a small-scale map is the presence of the rift in the northern Milky Way between Cygnus and Sagittarius; the rift appears exactly between the position of the star Deneb and the extreme right. This rift is due to the presence of opaque interstellar material that blocks the view.

APPROACHING THE GALACTIC CENTER— This photograph of the region around Sagittarius was taken with a lens of 25 cm (about 10 in.) focal length, and only a few centimeters in diameter. Invisible behind the cloud of stars and cosmic dust are large numbers of other stars belonging to the galactic center. The number of stars that can be observed in the most luminous part of the Galaxy is amazing.

INTERSTELLAR ATOMS—If the spectrum of a very distant star situated in the plane of the Galaxy is photographed, it is often apparent that among the absorption lines of the star's characteristic spectrum are additional very fine lines due to absorption by atoms in the space between the star and the observer. These lines, by their fineness, point clearly to the fact that the interstellar gas to which these atoms belong is quite cold and, therefore, absorbs only a single frequency. If the gas were hot, it would absorb a range of frequencies and its spectral lines would be broad and fuzzy like those of the star's characteristic spectrum. The multiplicity of fine lines implies that the absorbing gas is in the form of a cloud that is in turbulent motion (due to the Doppler effect), indicating that the atoms of the absorbing gas are receding from the Earth at different velocities. The most frequently observed absorption lines due to interstellar atoms are characteristic of calcium and sodium. The presence of hydrogen is revealed by the appearance of a spectral line corresponding to the emission of a radio wave of 21 cm wavelength. This interstellar material in the form of free atoms and fine dust accounts for a large part of the mass of the Galaxy.





THE SOUTHERN MILKY WAY—A modestly priced telescope or a pair of good binoculars will reveal a vast quantity of stars in the Milky Way. This photograph of the southern Milky Way was taken with a small telescope directed to follow the movement of the celestial sphere. The galactic region corresponds to Carina and Centaurus, constellations of the Southern Cross. The dark patch is the so-called Coal Sack, an area where the light of the stars is obscured by opaque cosmic dust. The gradual decrease in density from the center toward the edges is striking.

MILLIONS OF STARS—This photograph, taken with an objective lens of 2.5 m (about 8 ft) focal length, reproduces less than one hundredth of the area of the previous photograph. Nevertheless, many millions of stars are visible. A still more powerful telescope would reveal additional stars with the same density, despite the enlargement. However, it is not possible to photograph the whole of the Milky Way on this scale within a reasonable amount of time. Photographs such as this serve as starting points for more detailed exploration and study on a localized basis. Thus, they are of practical value to astronomers.

dust and gas in the atomic state; the rest is distributed over a large number of stars. The sun is a star of average mass, which implies that the Galaxy contains many billions of stars.

RADIO ASTRONOMY AND MODERN STUDIES

Only a part of the Galaxy can be observed directly. First, the presence of opaque interstellar material interferes with observation of the more distant stars. However, many stars that are not obscured and that should be visible are so distant that they cannot be seen even through the most powerful telescopes. A reflecting telescope with a mirror 91 cm (36 in.) in diameter can photograph perhaps one billion stars; a reflecting telescope with a mirror 500 cm (200 in.) in diameter can photograph many more stars, but centuries would be required to complete the work because of the small field that such a large instrument can cover. Among the most recent studies were those that led to the localizing of the various stellar populations within the galactic system. There are some galactic regions where the stars are massive, luminous, and interspersed with great quantities of dust and gas. In an astronomical sense, the stars in such regions are young, and the star population of such a region is described as Population I. In other regions, the stars are red, faint, of small mass, regularly distributed, and not mixed with interstellar dust and gas. The population of such a region is described as Population II. These two types of stellar populations are quite distinct within the Galaxy: the first appears predominantly in the spiral arms, while the second appears mainly at its center.

Because of the great density of interstellar dust and gas and the specific position of the sun within the Galaxy, it is not possible to reach the galactic center by optical means. Radio telescopes, however, can reach the galactic center from which the emission of interstellar material can be detected. In recent years, radio astronomers have detected in the Milky Way carbon monoxide, interstellar hydroxyl, ammonia, water, and formaldehyde molecules. Theoretical astrophysicists are working on interpretations of these observations. Radio astronomy makes it possible also to construct with precision a map of the entire galactic system.

Despite the fact that, today, man has made his first steps into space, it is not foreseeable that he will ever be able to move toward the distant and mysterious regions of the Galaxy.

STARS, GAS, AND DUST—With the same telescopic arrangement as that used for the photograph of the above illustration, far fewer stars are to be seen around the star Gamma in the constellation Cygnus than elsewhere. The reason is that here, together with a lesser though still large number of stars, nebulosity occurs. These nebulas are accompanied by opaque fine dust, and so prevent the view of the more distant stars, which in photographs of the Milky Way form the richest background.

CLUSTERS OF GALAXIES | remote continents of the universe

Whenever ancient man viewed the heavens, he must have felt confident that all the universe—the sun, moon, planets, and stars—revolved around the Earth on which he stood. Today, at the beginning of an era in which man has reached the moon on his first venturesome step into space, a far more humbling concept of Earth's place in the universe prevails. Man now knows that his Earth is merely a small planet revolving around a middle-sized star on the fringe of just one of uncounted billions of galaxies.

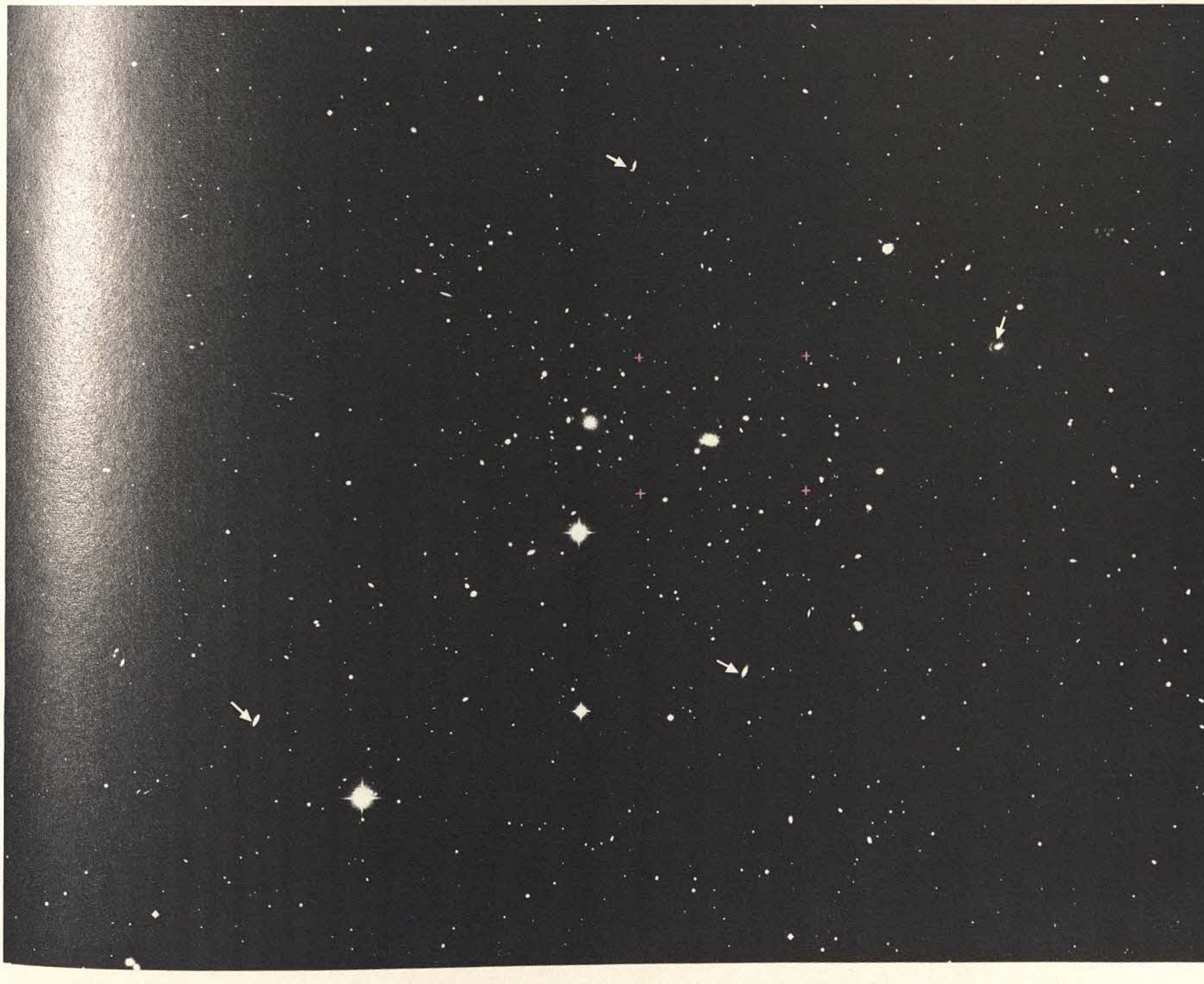
In the awesome geography of space, the dimensions of the Galaxy to which the solar system belongs—the Milky Way—stagger the imagination; and the distances of other galaxies are almost beyond comprehension. To comprehend even partially galactic sizes and distances, they must be related to the known dimensions of the solar system, because no other comparative yardstick exists.

The sun, for example, is approximately a hundred times larger in diameter than the Earth, and the distance between the Earth and the sun is about a hundred times the solar diameter. Light, at a velocity of 186,000 miles per second, spans this great distance in about eight minutes. The distance light travels in one year—nearly 6 trillion miles—is used

ONE OF THE CLOSER CLUSTERS OF GALAXIES—most of the clusters of galaxies concentrated in the center of the photograph (Illustration 1a) have quite small diameters and can be confused with stellar images. In many cases, however, the clusters have an ellipsoidal shape that distinguishes them from the round images of stars. Spherical clusters can be recognized by the nebular halos surrounding them. The stars in the foreground are part of the Milky Way; the telescopic image does not allow them to be clearly distinguished. The photograph was taken with the 48-in. Schmidt telescope at Mount Palomar.

Illustration 1b shows the central part of a cluster of galaxies in the constellation of Coma Berenices. This photograph was taken with the Mount Palomar 200-in. reflecting telescope.

1a



as the unit for measuring astronomical distances. The nearest star to the Earth is approximately 4 light-years away—about 24 trillion miles, or hundreds of thousands of times more distant than the sun. The more distant stars in the Milky Way, the Earth's Galaxy, are as much as 100,000 light-years away. This is the first leap from planetary to stellar dimensions. The second leap is from stellar to galactic distances. The stars of the Milky Way form a flattened ellipsoidal globe with a diameter of about 100,000 light-years—a Galaxy containing about 100 billion stars with masses larger than, smaller than, or approximately equal to that of the sun.

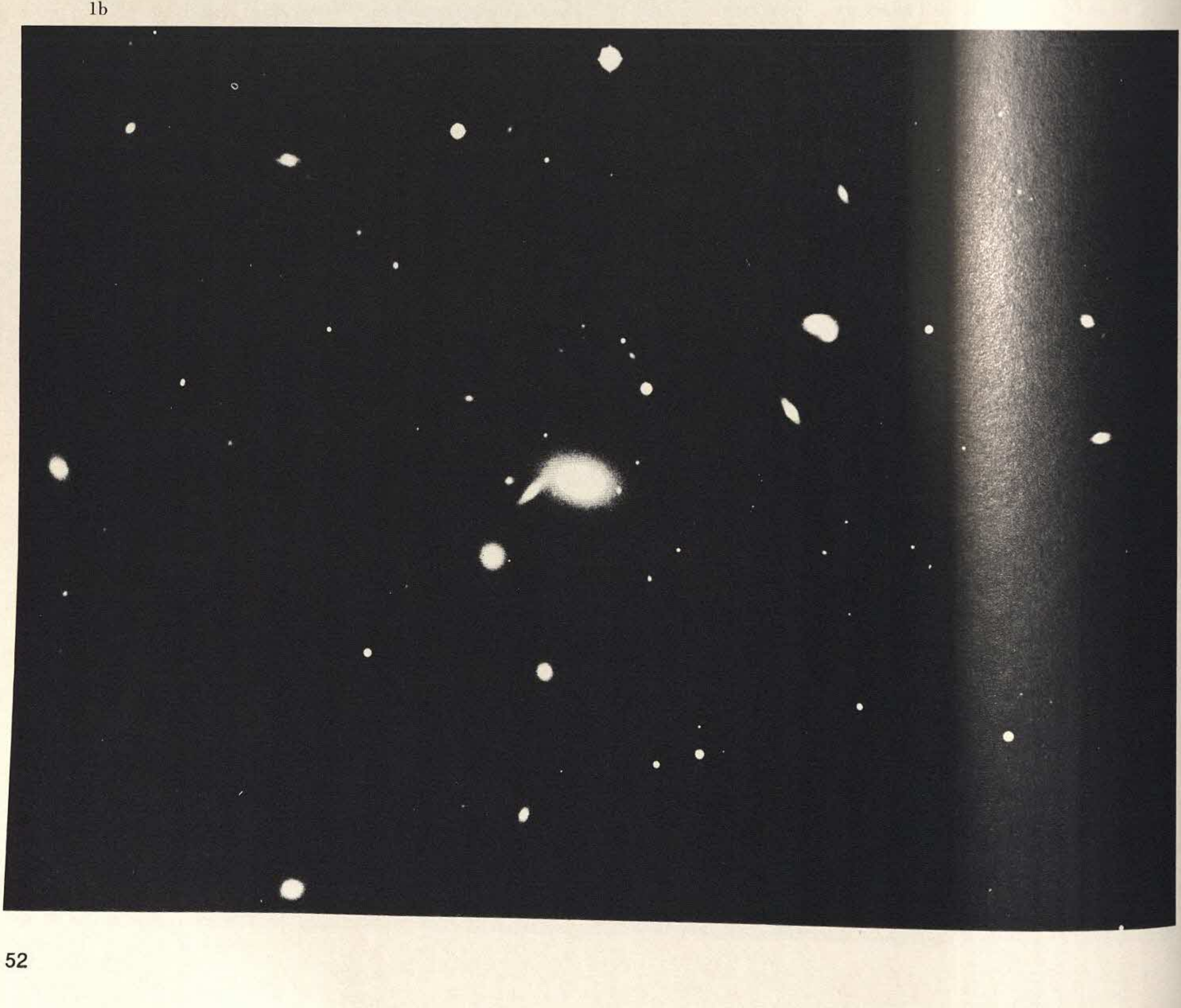
Outside the Milky Way, and separated from it by great reaches of empty space, are billions of other galaxies. The nearest galaxy, the Great Spiral Galaxy in Andromeda, is about 1.7 million light-years away. Using the most powerful telescope in the world—the Mount Palomar 200-in. reflecting telescope—it is possible today to estimate in hundreds of billions the number of galaxies in the universe. Many billions more may stretch beyond the observation limits of this telescope. Each of these galaxies contains a myriad of stars, varying from tens of billions to more than the 100 billion in the Milky Way.

A few of the galaxies beyond the Milky

(In Illustration 1a, the four red crosses mark the limits of the photograph in Illustration 1b.) In Illustration 1b, the stars of the Milky Way are much more easily distinguished from the galaxies than in Illustration 1a; these stars are plainly in the minority. The largest galaxy, an ellipitical type, stands out clearly in the center; other types of galaxies are clearly visible. The distances between galaxies in a cluster are almost always the same.

The Milky Way belongs to a smaller cluster whose members form the so-called local group of galaxies. Astronomers have known for several decades that certain galaxies close to the Milky Way appear practically stationary, while many others are in a progressive state of withdrawal that varies proportionally to their distance.

1b

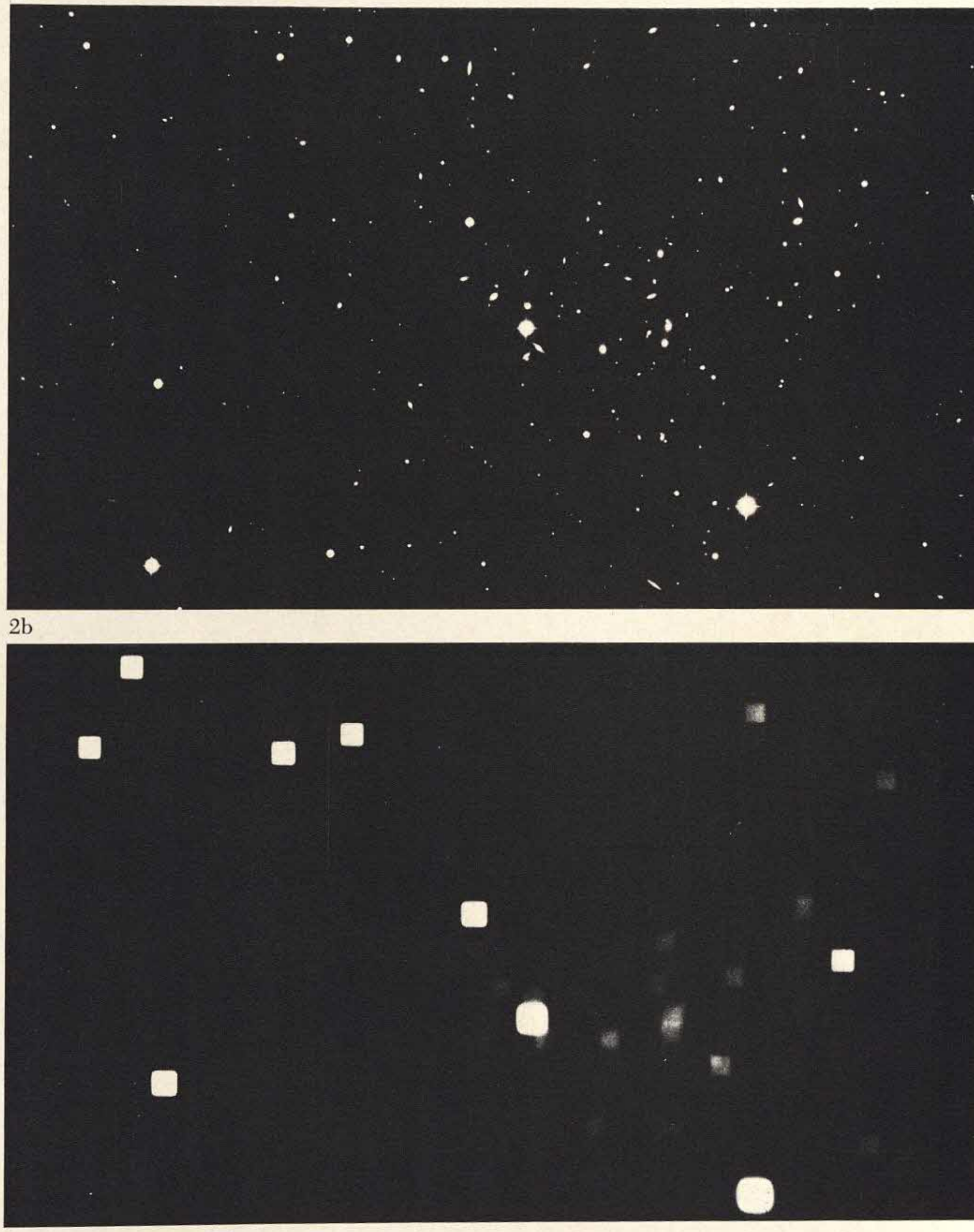


Way are visible without the aid of a telescope. Ancient astronomers noticed Andromeda and recorded it as a fixed star. While attempting to sail around Africa in the fifteenth century, Portuguese sea captains in the fleet of Prince Henry the Navigator sighted two galaxies in the sky of the Southern Hemisphere. Not knowing their true nature, the Portuguese named these galaxies Magellanic Clouds.

Not until development of the first telescopes were more galaxies discovered. Early astronomers, believing these galaxies to be clouds of gas, called them "nebulae." An eighteenth-century French astronomer, Charles Messier, was a devoted student of comets. Annoyed by the "gas clouds" that interfered with his telescopic observations from the tower of a Paris hotel, Messier charted 103 of the larger nebulas which he wished to ignore. Ironically, many of these nebulas that so annoyed Messier were proved to be galaxies that are identified today by using the letter M (for Messier) and a number, such as M31 for the Great Spiral Galaxy in Andromeda.

Other astronomers of Messier's time were unable to distinguish between gas clouds and galaxies. Nevertheless, in drawing up their astronomical catalogs and maps, these scientists realized that a number of nebulas—a high percentage of the visible total—were grouped in one zone of the sky near the constellation of Virgo. This was the discovery, which at the time was not fully appreciated, of the first clusters of galaxies. (The expression "clusters of galaxies" should not be confused with the term "galactic clusters," which refers to open star clusters within the Milky Way.) Other groupings were subsequently discovered by the nineteenth-century English astronomer, Sir John Herschel, as he compiled his catalog of 2,500 nebulas.

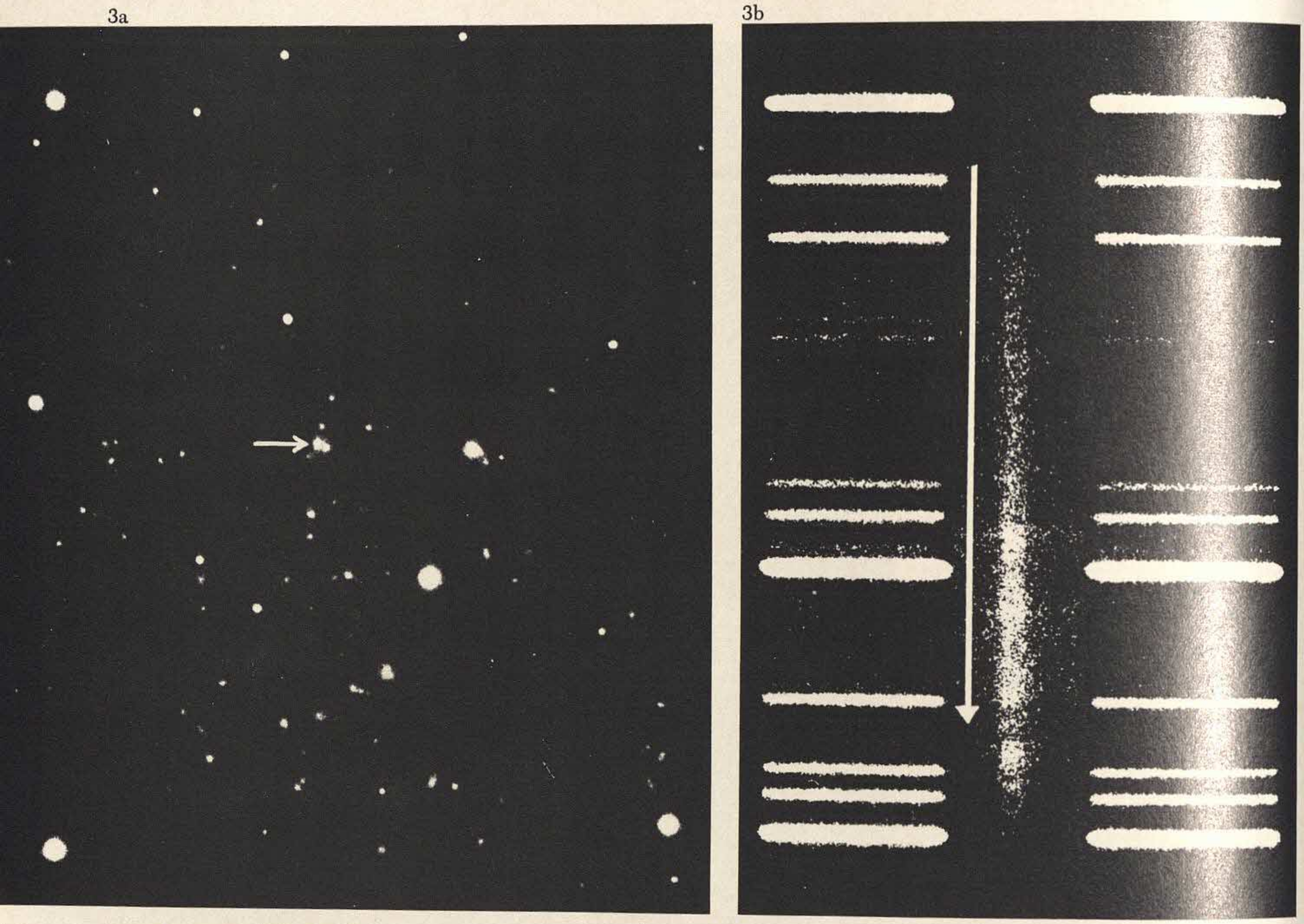
During the twentieth century, a systematic study of the celestial sphere has led astronomers to far wider knowledge of the number and variety of galaxies in the universe. Recent studies confirm that the galaxies of the universe are mostly grouped in clusters, and that the diam-



2a

2b

NEBULAR PHOTOMETRY—Astronomers know the luminosity of the stars in many galaxies. Therefore, once the total luminosity of an entire galaxy is known, the number of stars it contains also can be approximately determined. Both Illustrations 2a and 2b are photographs of the cluster of galaxies in Corona Borealis, 400 million light-years distant, and were made with the Mount Palomar 200-in. telescope. In Illustration 2b, however, the telescope was moved so that the light of the galaxies was spread into small squares on the film. In this way, astronomers determine the luminosity of each galaxy by measuring the degree of darkening at the center of each square on the negative plate.


3a

3b

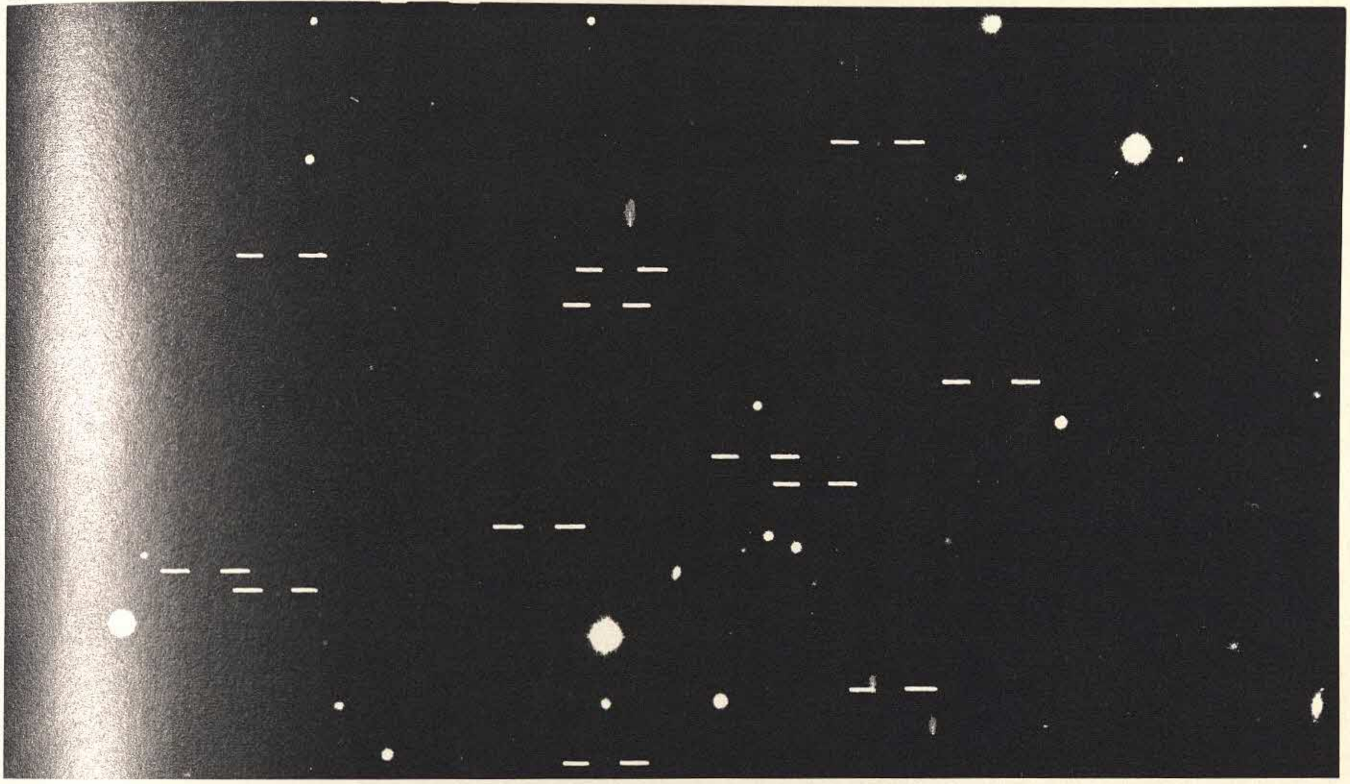
DETERMINATION OF RADIAL VELOCITY— This pair of photographs reveals how the distance of a cluster of galaxies is computed by radial velocity. Illustration 3a shows the cluster of galaxies in the distant constellation of Hydra. One of the galaxies (indicated by the arrow) is luminous enough for its spectrum to be photographed. Illustration 3b shows the spectrum of this galaxy; beside it is the spectrum of iron. By comparing the wavelengths of the lines, the shift of the galactic spectral lines toward red can be determined. From the amount of this shift, astronomers have deduced that this cluster is receding from the Milky Way at a velocity of about 38,000 miles per second, or approximately a fifth of the speed of light. This velocity corresponds to about 400 million light-years.

eter of individual clusters reaches tens of millions of light-years.

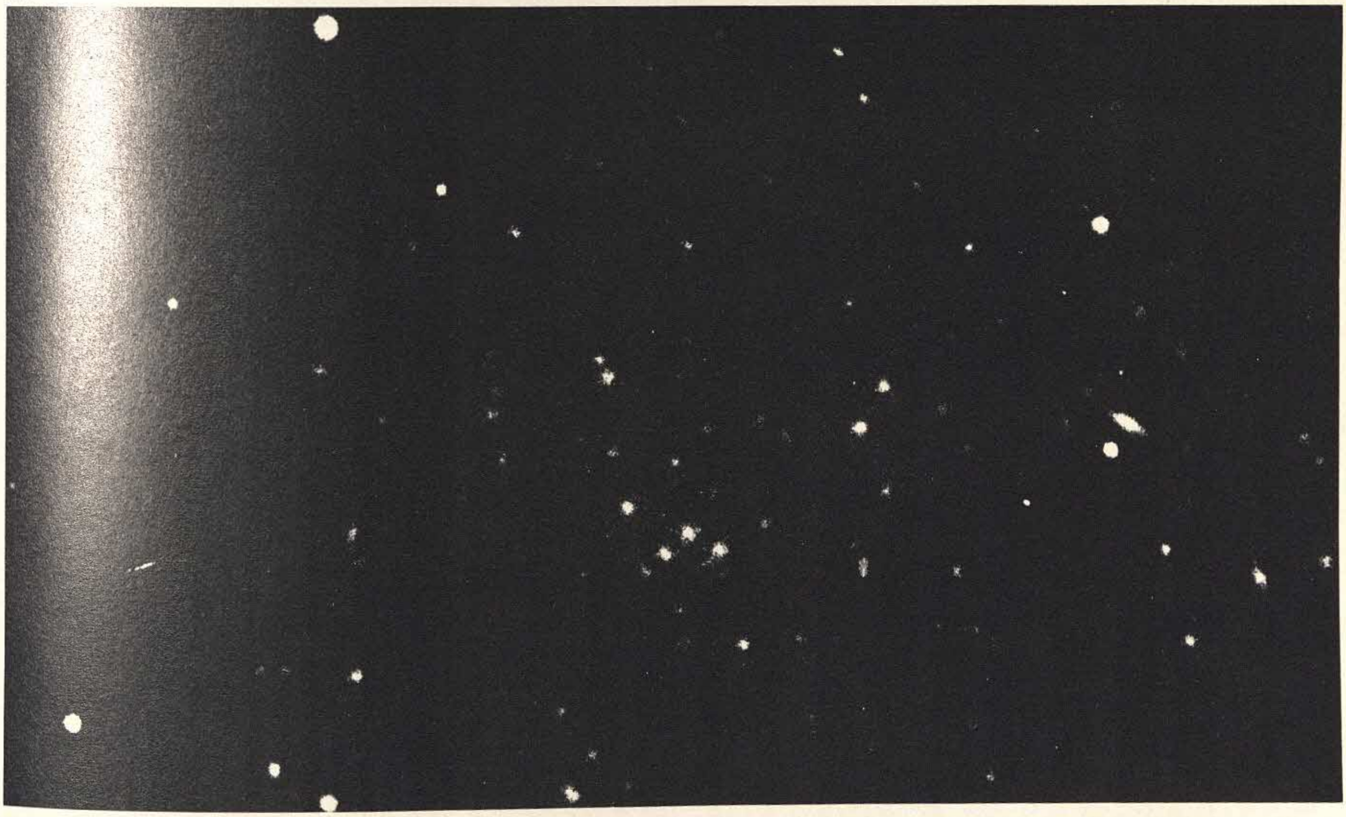
The clusters of galaxies are, beyond doubt, the largest celestial systems in the universe. Thousands of these clusters are known, suggesting to some astronomers that the clusters, and not individual galaxies, may be the fundamental building blocks of the universe. Many different studies of clusters of galaxies have been undertaken. These studies have sought to count the number of galaxies contained in each cluster and to analyze the types of clusters. They have disclosed that the clusters form part of the general recessive movement of the galaxies away from the Milky Way. In the constellation Virgo, for example, a large cluster of galaxies about 22 million light-years distant is hurtling away from the Milky Way at 750 mi per sec, while a cluster in Hydra, 1 billion light-years distant, is speeding away at a velocity of 38,000 mi per sec, about one-fifth the speed of light.

Expansion of present studies depends on the possibility of developing more powerful telescopes capable of observing more closely the individual galaxies that comprise these giant celestial groupings. In the next few years it may be possible to reach out to still more remote points of the universe. However, it is also possible that the limits reached today in astronomical observation may be close to the maximum distance that can be attained in the near future. Greater distances can be overcome by use of radio observation; but for the present, the optical limits of the universe are marked by such faint clusters of galaxies as Hydra and Pisces, several billion light-years from the Earth.

4a



4b



MORE DISTANT CLUSTERS—This pair of photographs illustrates the observational methods used to estimate the distance of the more distant galaxies. The paired lines indicate the positions of the galaxies photographed; these appear as tiny luminous images. Close study of the photograph reveals that each image is made up of a small group of grains of photographic emulsion. A more powerful telescope, in combination with a prolonged exposure and a more sensitive emulsion, would not clarify this image, which would be confused with the grains of photographic emulsion sensitive to the light from the background of the faintly luminous sky. An observatory placed outside the Earth's atmosphere, which interferes with optical observations, could resolve certain photographic problems of this type.

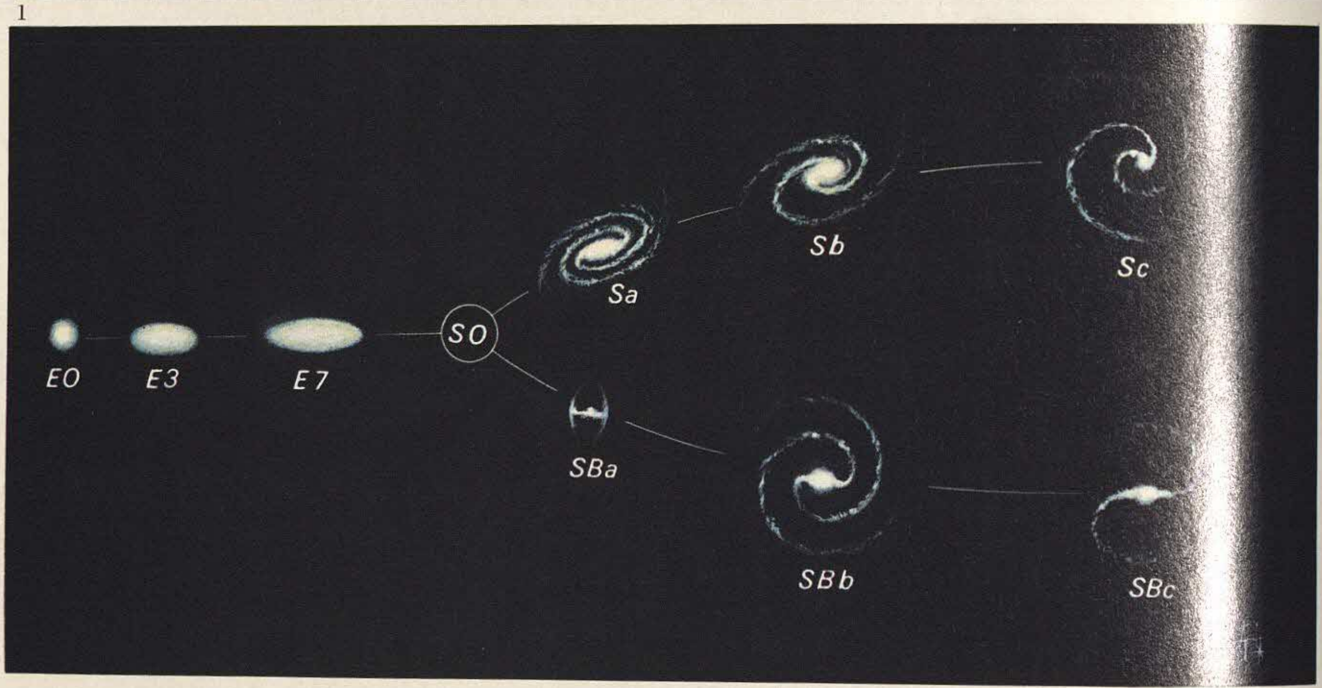
The galaxies in Illustration 4a are in the constellation of Coma Berenices, and are nearly 2 billion light-years distant. Their luminosity is about that of 23rd or 24th magnitude stars.

Illustration 4b shows one of the most distant celestial bodies known. Located in the constellation of Pisces, it is a cluster of galaxies in which only the most luminous galaxies can be optically observed. This cluster is nearly 3 billion light-years distant, and each galaxy appears as a few bright grains of emulsion hardly distinguishable from the impressions produced by the luminous background of the celestial sphere.

CLASSIFICATION OF GALAXIES

ellipsoids and spirals beyond the Milky Way

1



HUBBLE'S CLASSIFICATION—Using the largest telescopes available, at Mount Wilson and later at Mount Palomar, Edwin Hubble offered the first rational classification of galaxies, an outline of which appears in this illustration. At the left are shown, with the letter E, the elliptical galaxies, subdivided according to variations from the spherical in their telescopic appearance: the perfectly spherical are classified E0, the most elongated or lenticular as E7. Next to the right, beginning at S0, are the two branches of spiral galaxies: those on the upper branch are the pure spirals, while those on the lower branch are the barred spirals. In each case, the sequence proceeds according to the openness of the structure, from Sa (or, in the barred branch, SBa), in which the spiral arms are quite close to the central nucleus, to Sc (or SBc), in which the arms are thinner and less coiled. A fourth type, not shown here, is labeled I, for irregular; and if, despite its irregularity, a galaxy of this type has some distinguishing characteristic—such as radio emission, or zones emitting a predominantly red or violet color, or the structure of a double nebula—the letter p is added to signify "peculiar."

Until well into the twentieth century, astronomers believed that the entire universe consisted of the star system known as the Milky Way (or Galaxy, from the Greek word for "milk"). The use of astrophotography and improved reflecting telescopes made it possible, for the first time, to discover celestial objects beyond the Galaxy, objects therefore called extragalactic. These had the appearance of objects generally classified as nebulas—"clouds" of starry matter—and were at first called spiral nebulas, because of their apparent shape, or extragalactic nebulas, to distinguish them from real nebulas within the Galaxy. Eventually, largely because of the discoveries of the American astronomer, Edwin Powell Hubble, it was realized that these so-called nebulas were in fact separate galaxies, and that they had various shapes by which they could be classified.

Before the extragalactic "nebulas" were so identified, they had been classified along with true nebulas and star clusters. Among the earliest catalogs was that of Charles Messier, a French astronomer, who, in 1781, listed 103 such objects. Various nebulas and galaxies are still referred to by their Messier listing—for example, the Crab Nebula, M1, cataloged by Messier. The first important study of nebulas was made by the English astronomer William Herschel, who listed about 2,500 nebulas. His son, John Herschel, continued this work and issued an expanded catalog of nebulas in 1864, which became the basis in turn of the *New General Catalogue of Nebulae* (abbreviated NGC and still in use), published in 1888.

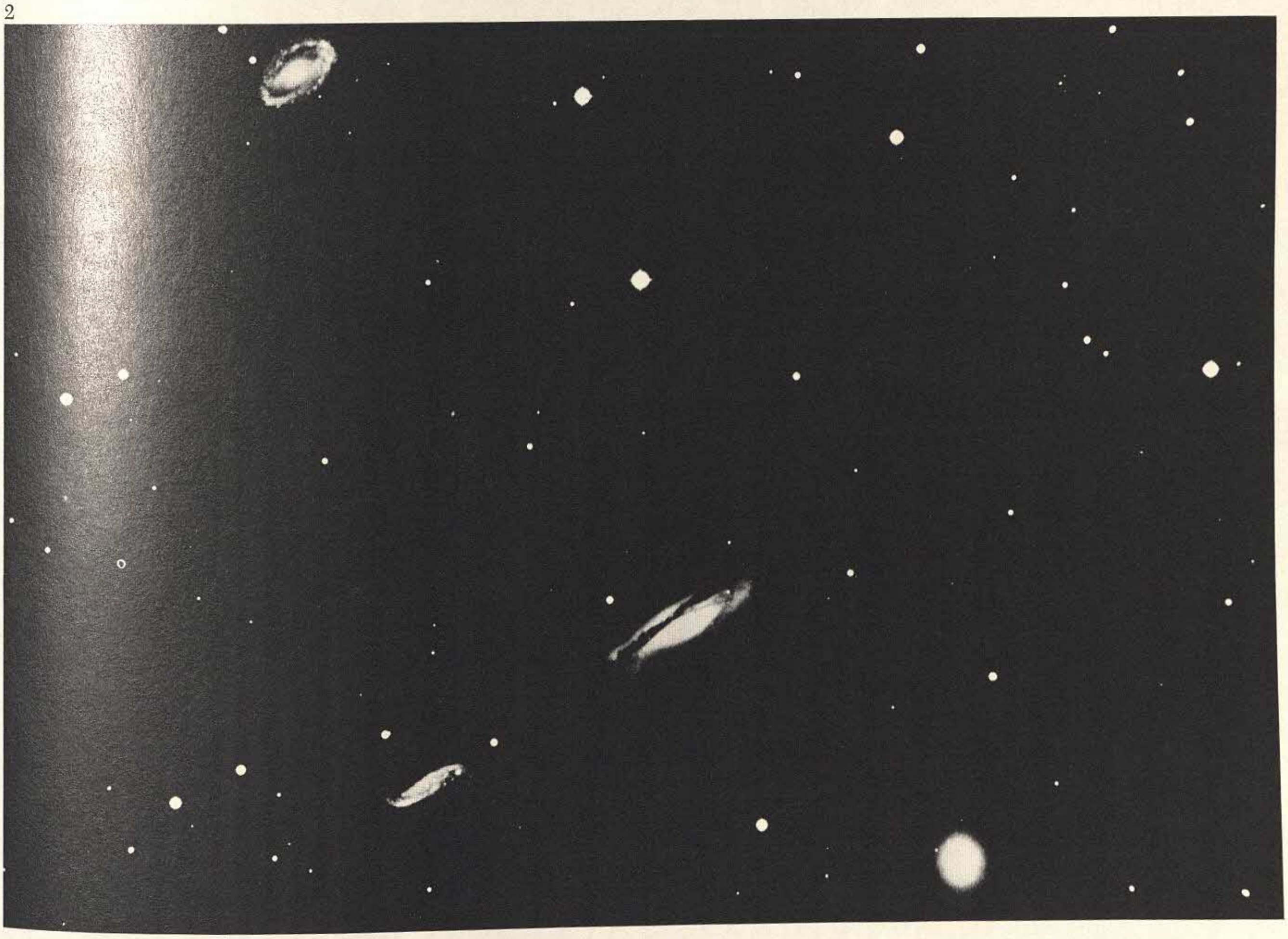
The younger Herschel used a 48-in. reflecting telescope, but in 1845 an Irish astronomer, William Parsons, Earl of Rosse, constructed a 72-in. reflecting telescope that was to remain the largest telescope until a 100-in. reflector was set up on Mount Wilson in California in 1917. The Herschels and Rosse examined the nebulas with increasing care for detail, but they failed to distinguish between galactic nebulas and galaxies beyond the Milky Way. Yet even Rosse was able to observe that M51 in the constellation of Canes Venatici, which had appeared in earlier telescopes as two roundish patches—one more luminous than the other—was actually very complex. The luminous patch, apparently surrounded by a ring, showed up in Rosse's powerful telescope as a bright nucleus from which spiral arms uncoiled; this was the first of what became known as the spiral nebulas. Soon it was observed that many nebulas were ellipsoidal, some were almost circular and others were so elongated as to be described as lenticular (lens-shaped); some of the latter also had extensions along the axis of the central portion that were called bars. Still others were entirely irregular, although when the true nebulas were distinguished from the galaxies, it became evident that relatively few irregular galaxies were visible and that their irregularity differed from that of the diffuse nebulas within the Milky Way. These shapes became the basis of the first modern classification made by Hubble in 1926.

Observations of the galaxies continued from observatories such as those at Mount Stromlo in Australia and, in California, the Lick Observatory on Mount Hamilton and those on Mount Wilson and Mount Palomar. The galaxies observed through these telescopes have been classified as to their shape and structure, which have provided clues concerning their age and evolution—for galaxies, like other celestial objects, have an origin, periods of youth and old age, and perhaps extinction.

Modern study of nebulas, both galactic and extragalactic (the galaxies), depends greatly on auxiliary equipment used on large telescopes. The most useful auxiliary instruments are spectrographs of several kinds, photometers, and photoelectric scanners that can make absolute intensity measurements as a function of wavelength. All the observatories at which nebular observations are made use these various types of instruments.

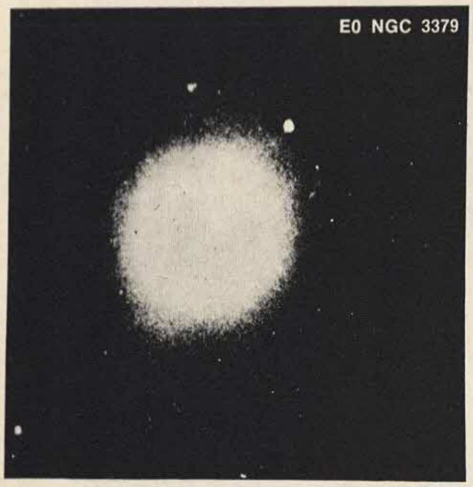
A VARIED GROUP OF GALAXIES—This fine photograph of four galaxies in the constellation Leo was taken by the 200-in. Hale telescope on Mount Palomar. Usually types are quite similar in groups of galaxies, but in this instance considerable variation exists. The galaxy at the upper left corresponds to an E0 or E1 in Hubble's classification; that at the upper right is SBc; the one just above center is S0 or Sa; and that at the bottom right is SBb. It should be realized that, telescopically, galaxies usually appear in profile (or edge-on) or at an angle more often than from above (as in Illustration 1), where their structure would be more apparent.

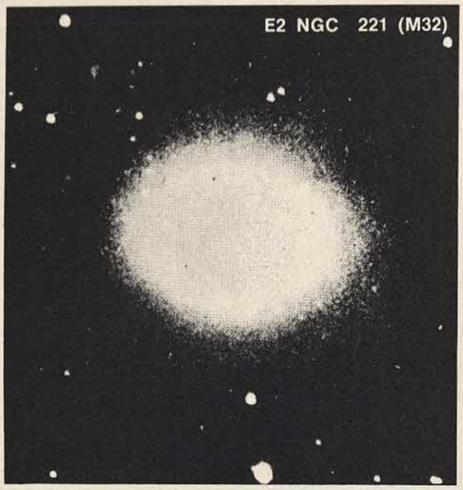
2

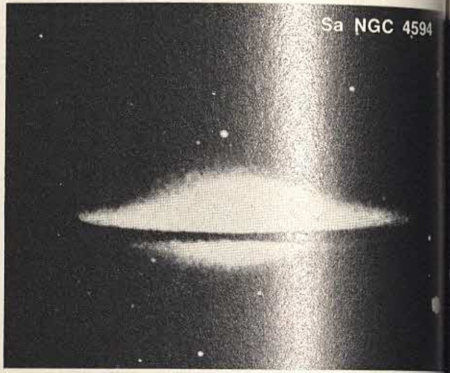


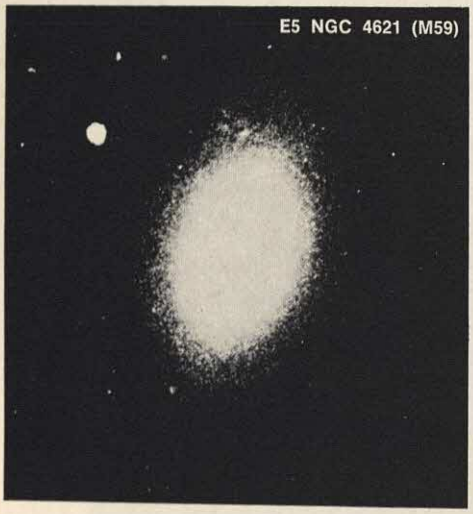
3

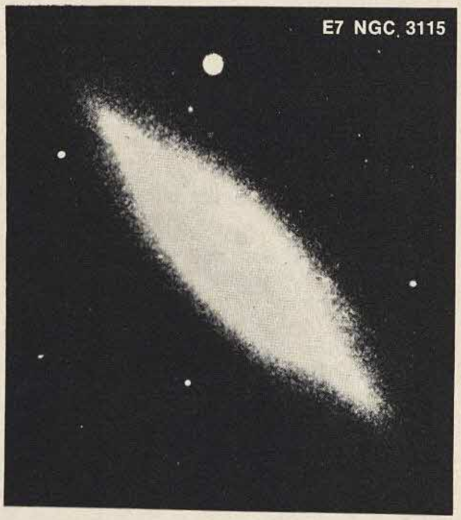
A DOZEN REPRESENTATIVE TYPES—These separate photographs of 12 different galaxies illustrate the more important variations, all classified according to Hubble, and with their NGC (and in some cases their M) listings. It is not always easy to understand from such photographs why the galaxy has its particular classification; NGC 4594 is Sa, even though no spiral arms are apparent. These would appear if the galaxy could be seen from another angle, as they do appear on analogous galaxies. NGC 2859 is classified SBa, rather than

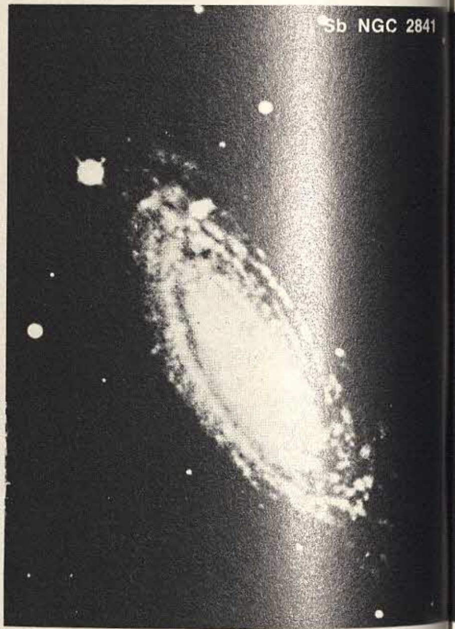

E0 NGC 3379

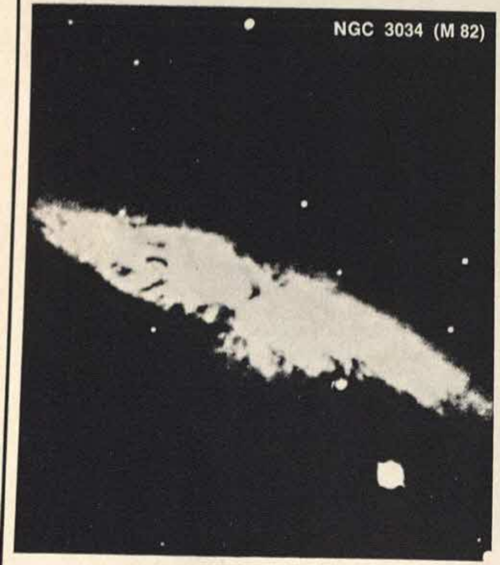

E2 NGC 221 (M32)

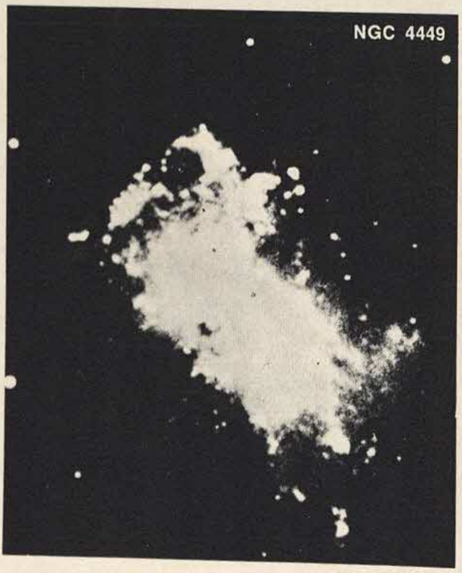

Sa NGC 4594

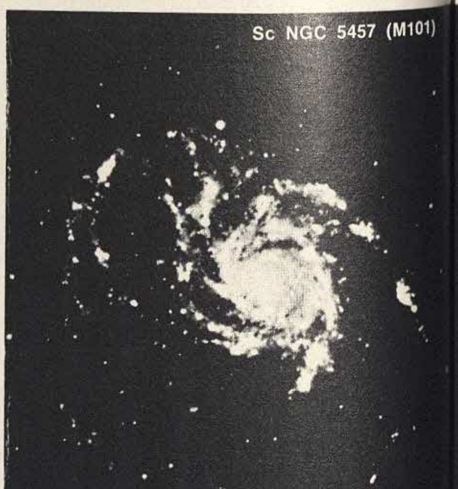

E5 NGC 4621 (M59)


E7 NGC 3115

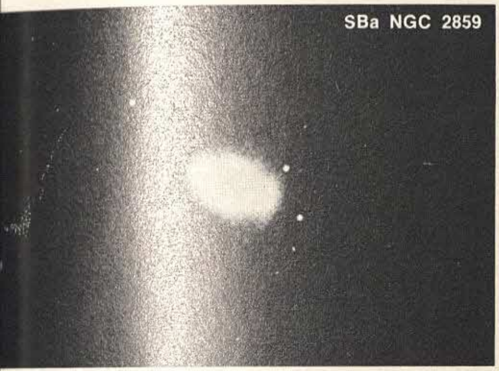

Sb NGC 2841


NGC 3034 (M 82)

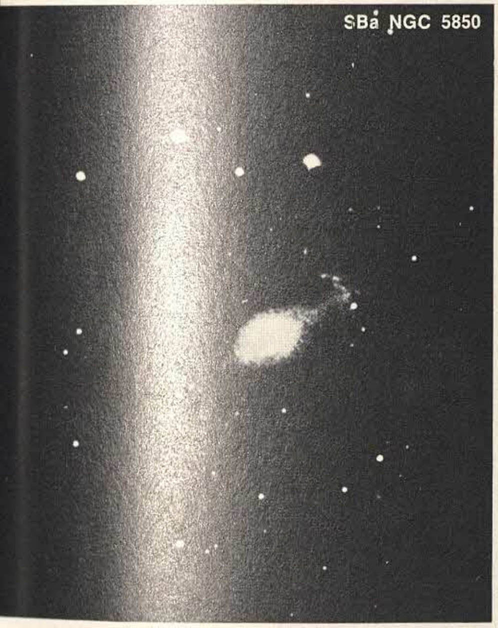

NGC 4449


Sc NGC 5457 (M101)

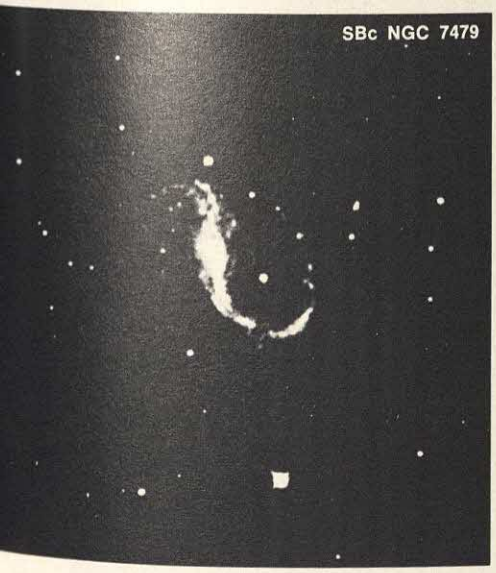
an E or ellipsoid type, because of faint bars projecting from its center. NGC 2841, a spiral, has extremely slender arms. A particularly fine spiral is shown in NGC 5457, an Sc.



SBa NGC 2859

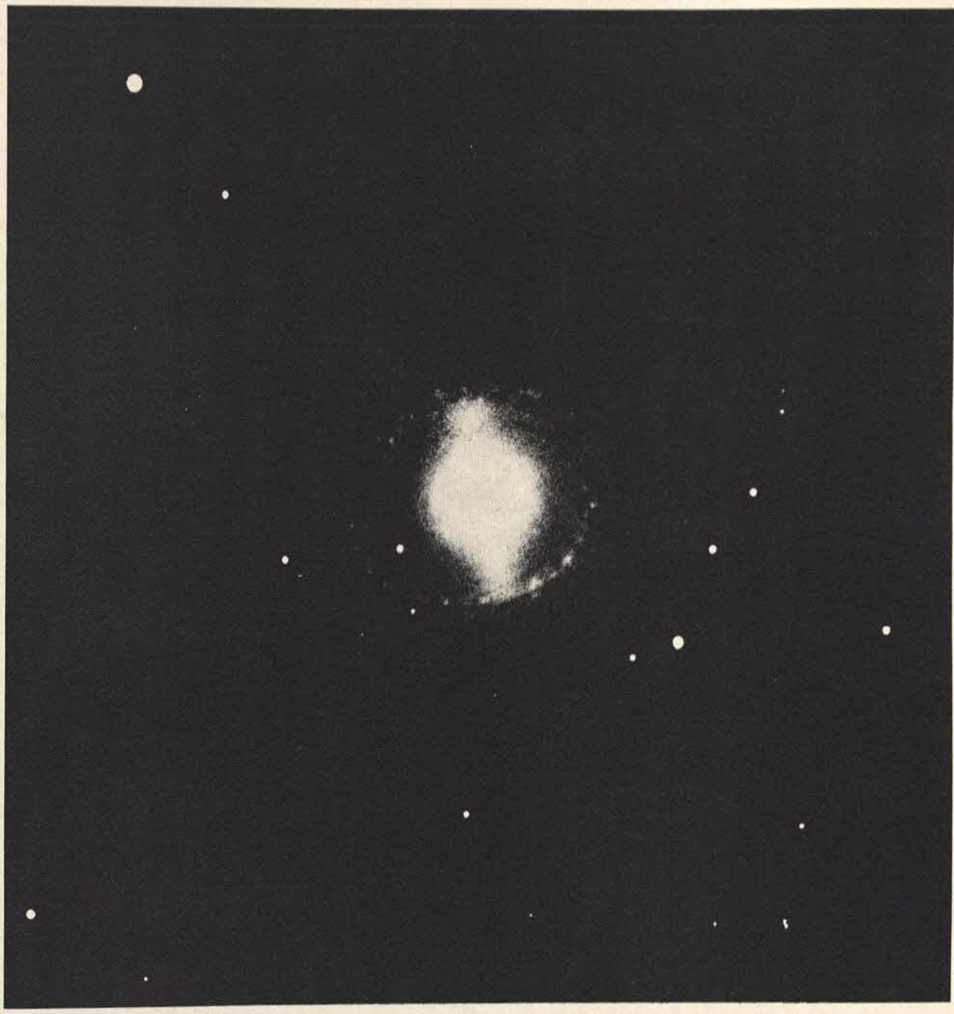


SBa NGC 5850



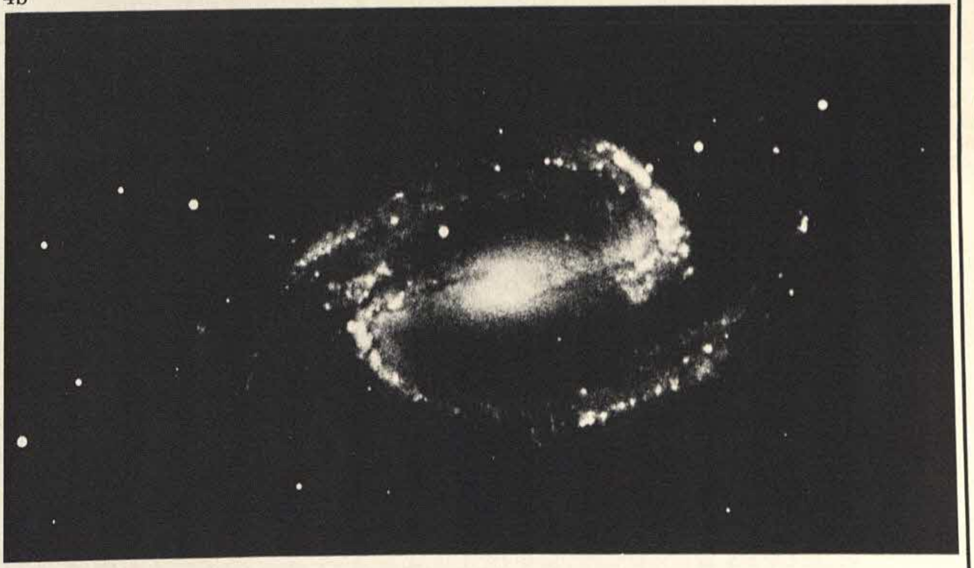
SBc NGC 7479

4a

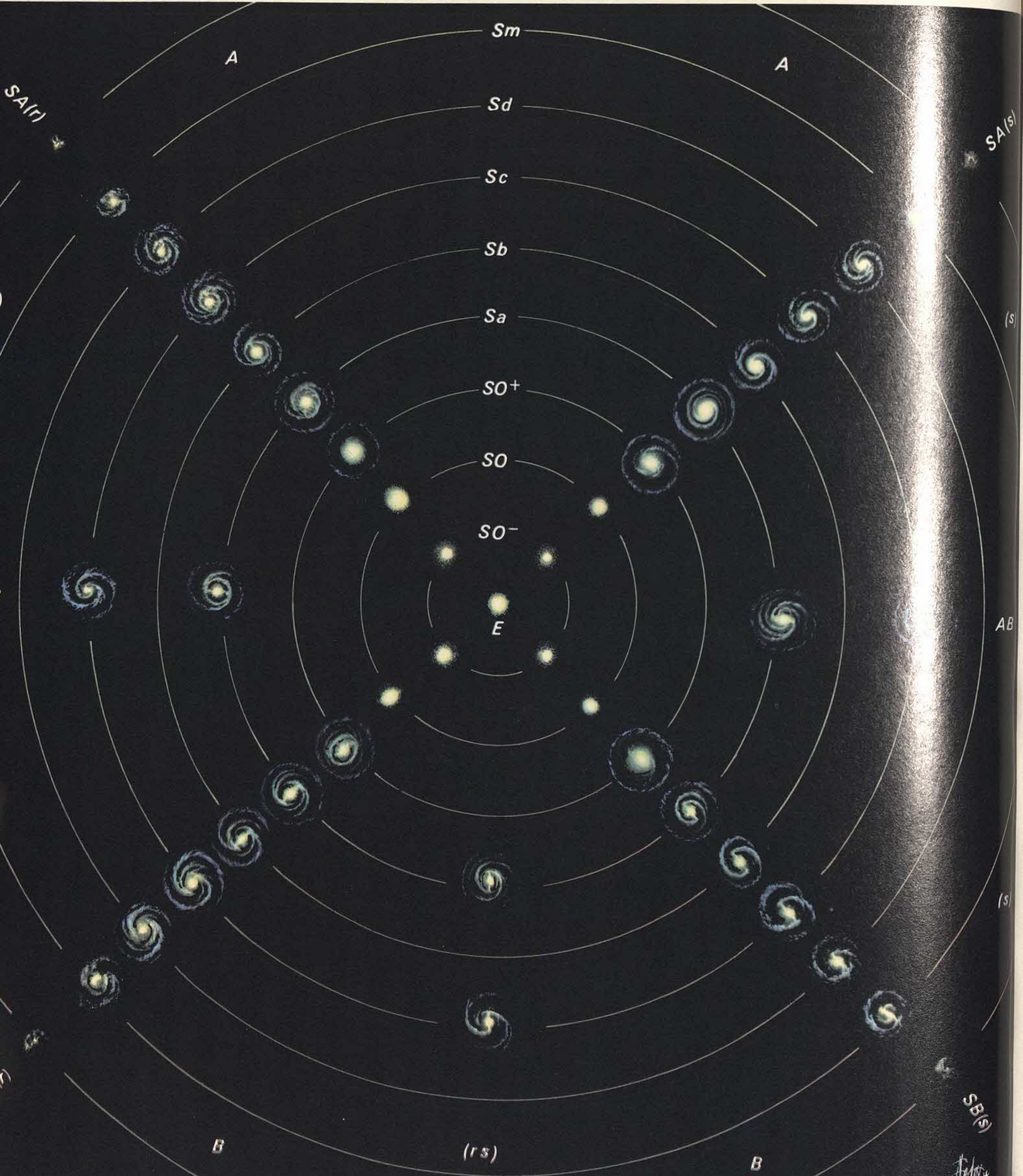


TWO BARRED SPIRALS—Although these two galaxies are classified SB, they appear very different. The galaxy in Illustration 4a is a bright center surrounded with a thin ring—actually composed of some billion stars—and is classified SBa. The galaxy in Illustration 4b, although it does not have a very open structure, is classified SBc because the arms do not begin at the center, but at the ends of the bar extending from each side of the center. Such examples indicate the need for a more elaborate classification system.

4b



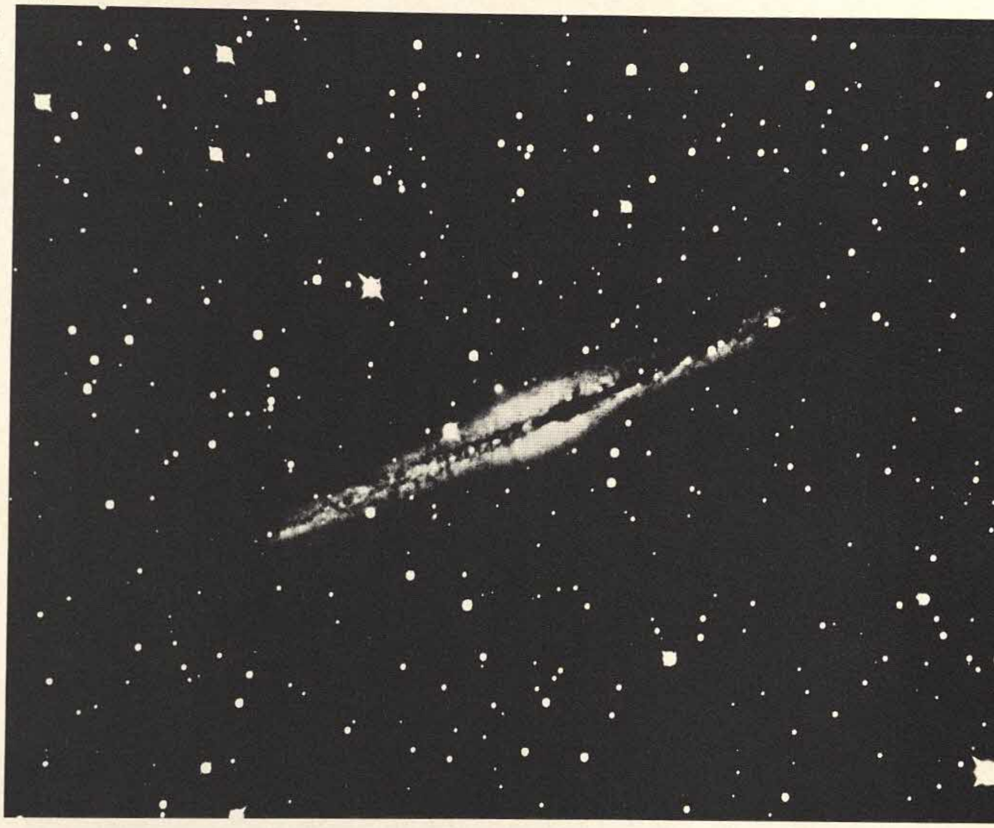
5a



THE REVISED CLASSIFICATION—The classification represented in Illustration 5a is a major attempt to describe all possible types of galaxies and especially to assign code letters to intermediate types. In the center is the perfectly symmetrical shape, a sphere, and in gradual succession toward the edges are the shapes of greater complexity, until complete irregularity is reached. In the upper part are spiral galaxies; in the lower part are barred spirals; and across the center from left to right are intermediate types. In order to determine the code letter applicable to a galaxy, its shape should be identified in the illustration; its place in one of the sectors, together with its distance from the center of the diagram, indicates a corresponding grouping of letters. Other letters can be added if the galaxy has some peculiar characteristic.

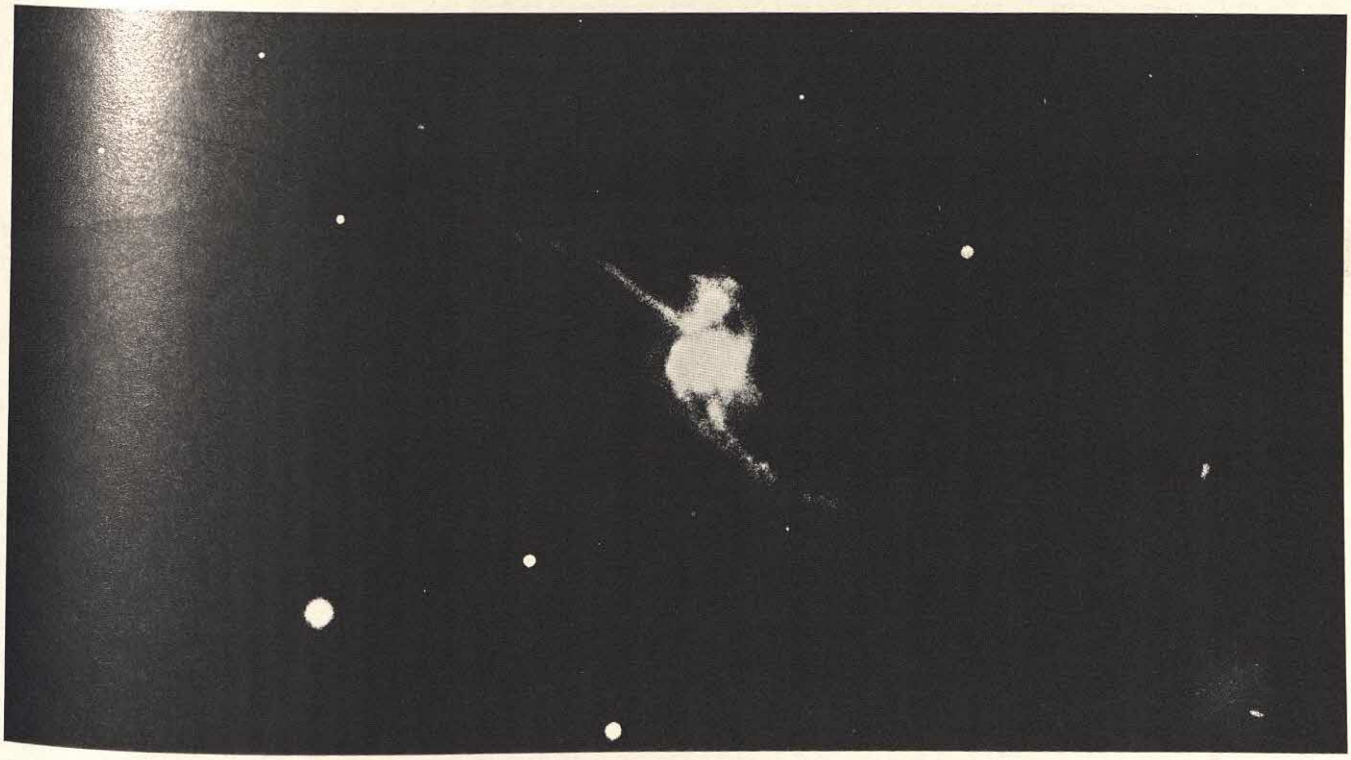
The galaxy in Illustration 5b is NGC 891 in Andromeda. According to the revised classification, this would be of the type SA(s)b(sp). Each of these letters indicates a particular feature of this galaxy, which is seen here almost edge-on.

5b



A "PECULIAR" GALAXY—The galaxy in this photograph, NGC 2623, exemplifies a type that cannot be identified completely in any classification system. It would be an Sc, except for the cluster of material at its center, the form of which is not easily classified; therefore, it is designated as Sc_{pec}—that is, peculiar. This galaxy emits strong radio waves, a manifestation of disturbances inside the galaxy. It should be noted that both perceptible peculiarities and those indicated by radio emissions need to be shown when classifying a galaxy.

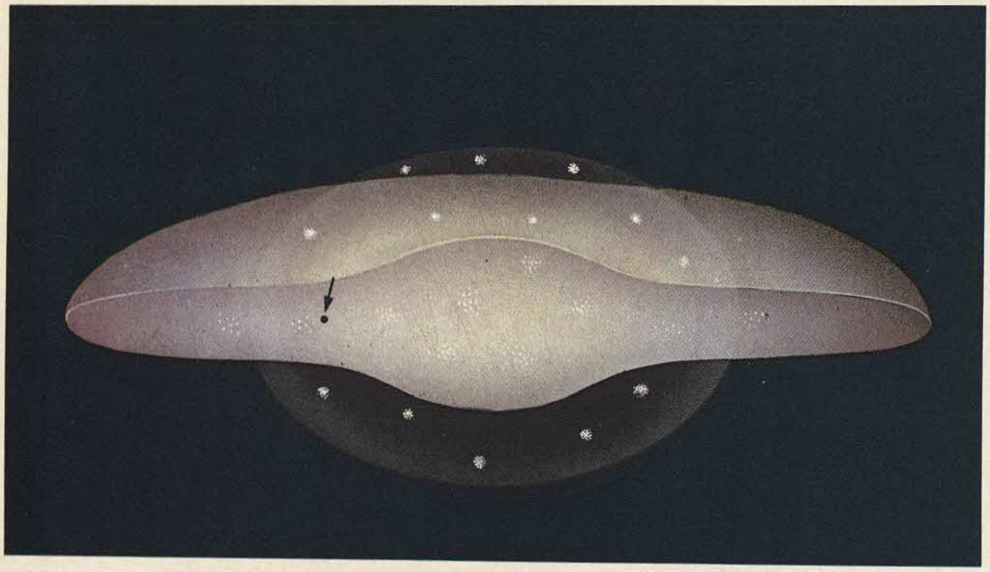
6



GALACTIC CLUSTERS | groups of stars

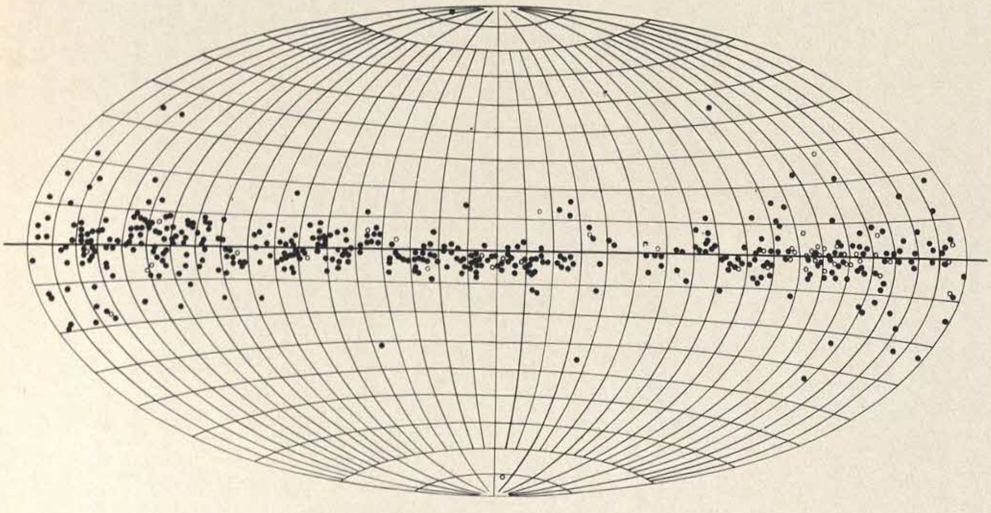
WHERE GALACTIC CLUSTERS CAN BE OBSERVED—This illustration (with an arrow indicating the position of the sun) shows that galactic clusters are distributed in the zones of the Milky Way, which appear to be nebulous because they are rich in stars. Many stars are seen around the sun, some of them forming galactic clusters. When a cluster is near the sun, it shows up distinctly against the background of other, weaker stars. When it is more distant, it may be confused with the large number of stars in the galactic background. In the first case, such a cluster is fairly easy to observe, while in the second case, it is fairly difficult. Because of this, and because interstellar dust limits vision in the galactic plane, a limited number of galactic clusters is known. Most of the galactic clusters that populate the Galaxy have never been discovered; those that are known are all relatively close to the Earth.

1



THE DISTRIBUTION OF GALACTIC CLUSTERS—For reasons shown in the preceding illustration, the only well-known galactic clusters are those in a limited band of space surrounding the Earth. All of these are shown in Illustration 2. This map of the celestial sphere does not have the poles and celestial equator as coordinates; instead, the galactic poles and the median plane of the Galaxy are illustrated, showing that the galactic clusters are concentrated near the galactic equator. If a telescope is pointed at the Milky Way and moved at random, a strong probability exists that the observer will see galactic clusters.

2



During the 1940s, astronomer Walter Baade of the Mount Palomar Observatory in California advanced a revolutionary concept of two separate star populations. One is an old population, comprised of halo stars and globular clusters, which are present in areas of space devoid of the dust and gas clouds from which new stars can be born. The other is a younger stellar population, comprised of disk stars and galactic clusters, sometimes called open star clusters. (The term "galactic clusters" refers to open star clusters within the Milky Way, and should not be confused with the expression "clusters of galaxies," which refers to groups of galaxies outside the Milky Way.) Many of these galactic clusters are surrounded by great quantities of star-building dust and gas clouds.

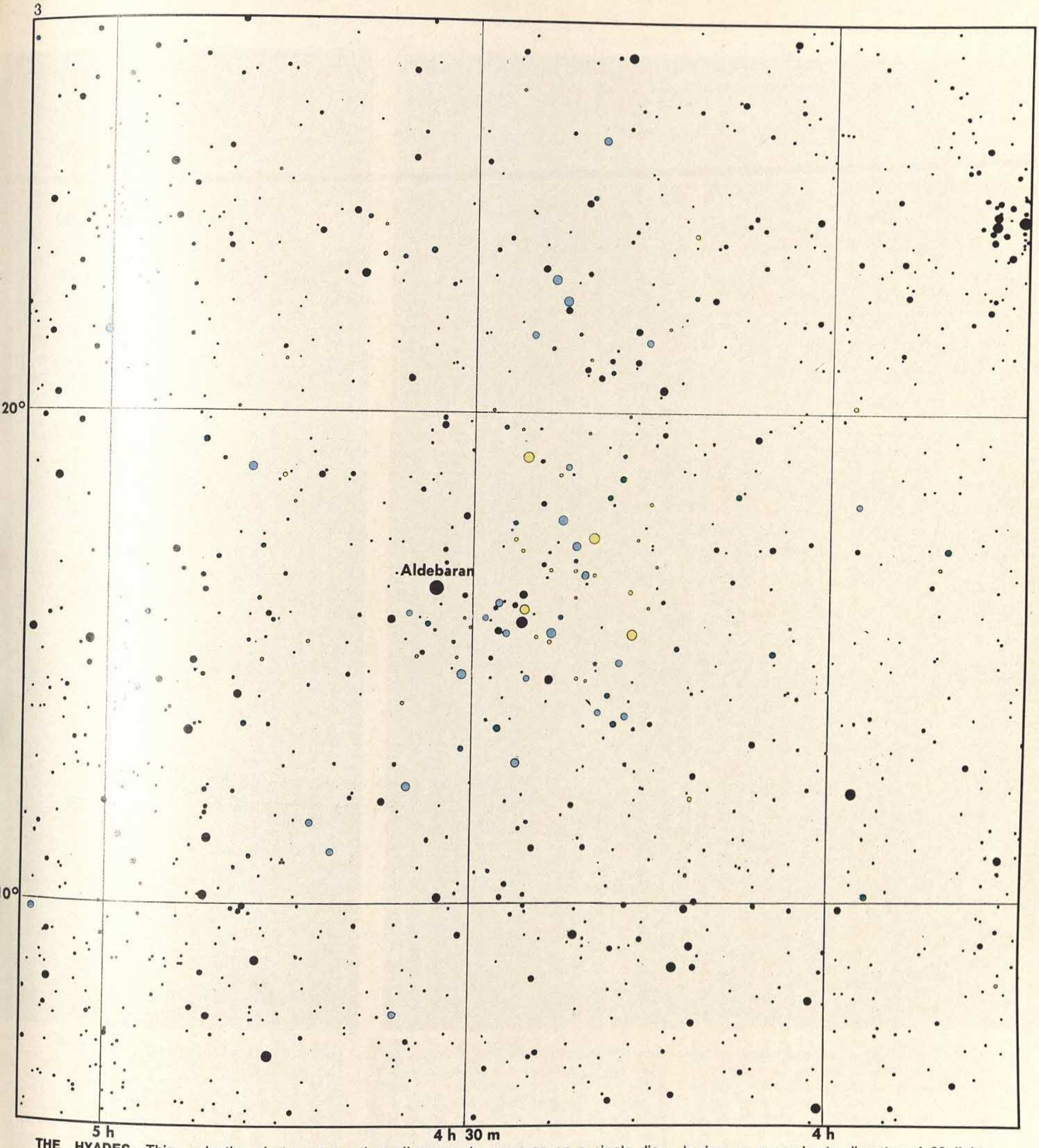
Some galactic clusters were known by the ancient Greek and Roman stargazers. The ancients could not explain the gravitational forces that held these clusters of stars together, but they considered them among the most interesting of the celestial bodies.

THE MYSTERY OF THE ORIGIN OF STARS

After the development of the telescope, many generations of astronomers devoted their time to discovering and cataloging new stars. This, in itself, was a monumental task, for it is estimated that, in the Milky Way, some 100 billion stars are spread out in space in the shape of a biconvex lens. From Earth, only a few thousand of these stars are visible to the naked eye.

In the present century—under the leadership of England's Sir Arthur Stanley Eddington in the 1920s, and Baade two decades later—astronomers turned their attention to the nature and origin of stars: what are they and how did they come into being?

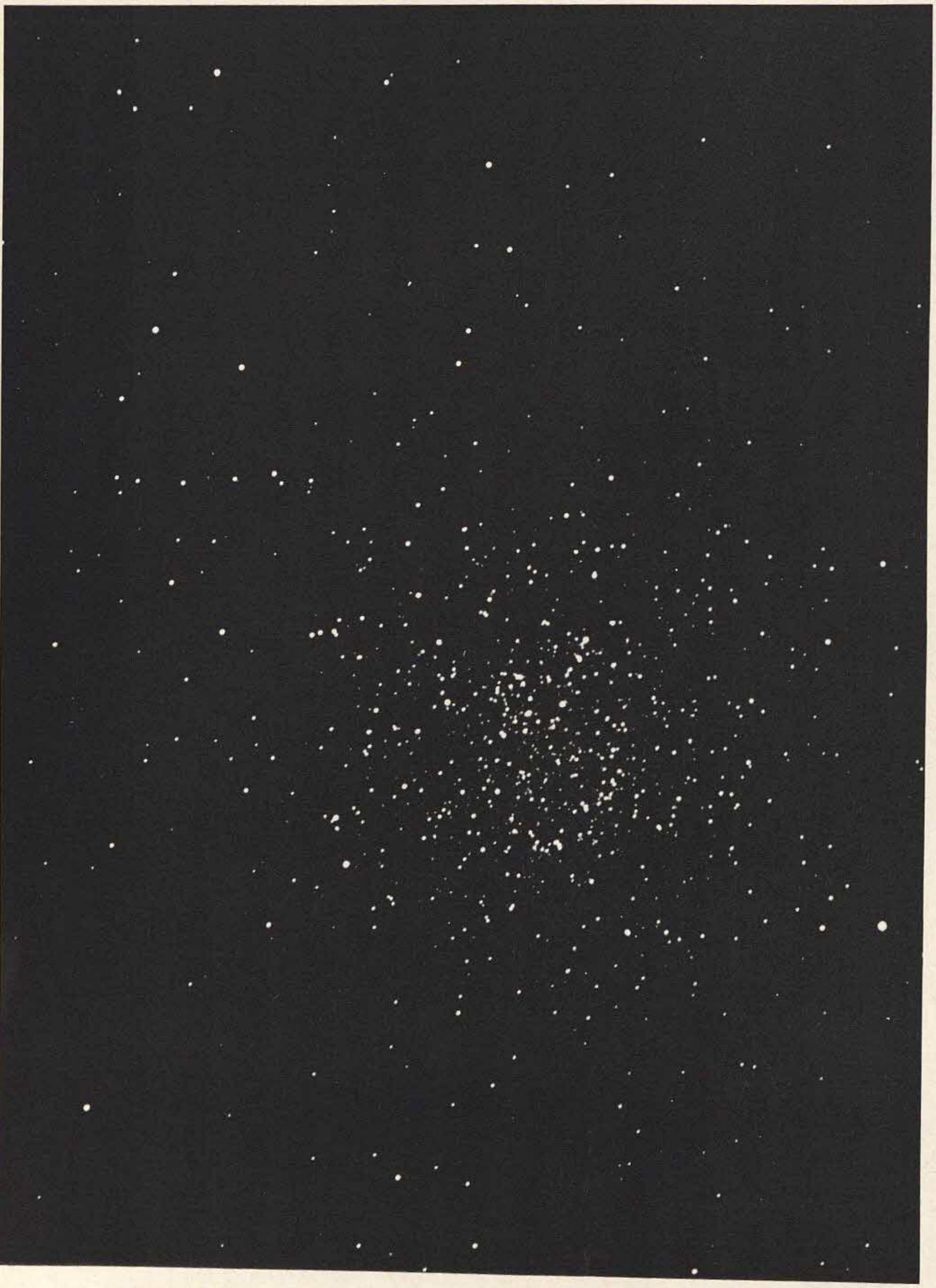
In recent years, hundreds of scientists have expanded Baade's concept, intensifying studies of the globular and galactic clusters. These studies, in which the brightness and color of thousands of stars were measured and plotted, revealed that galactic clusters vary widely in age. Some galactic clusters are believed to be at least three times as old as the Earth's sun.



THE HYADES—This galactic cluster was known by the ancient Romans. The works of Roman poets refer to the belief that the Hyades at its most brilliant was considered a harbinger of rain. This belief was probably due to the fact that optimum evening visibility of the Hyades occurs in autumn, a rainy season. The Hyades is a cluster of about 350 stars moving toward some distant point in space. If the speed of the stars in this cluster is indicated by arrows, it can be seen that they all appear to converge on a single distant point of recession. The effect is one of perspective, and is similar to the apparent convergence of railway tracks in the distance. Not all galactic clusters, however, show a point of convergence in the motion of their stars. In some cases, especially because of the vast distances involved, the motion of the stars is not measurable.

About half the stars that make up the Hyades cluster are concentrated in a sphere having an approximate diameter of 20 light-years. Their distance from the sun is about 120 light-years. However, these are small distances compared to the diameter of the Galaxy, which is estimated to be about 1,000,000 light-years. The stars of the Hyades cluster are indicated by colored disks, while those not belonging to the cluster are indicated by black dots. The colors show the few spectral classes of stars in this cluster: yellow corresponds to class C, blue to class A, and green to class F.

4



5

DISTANT CLUSTER—This photograph shows a very distant cluster in the constellation of Libra, many thousands of light-years from the Earth. The cluster has a very regular shape, yet the weak concentration of stars at the center is a special characteristic. Even where they are most dense, the stars appear well separated. Many other stars in this cluster are not observable, even with the very large telescope through which this photograph was taken. In some cases it is possible to determine how many times the mass of the cluster is greater than that of the sun; thus, if the stars composing the cluster are, on the average, as heavy as the sun, the total number of stars can be calculated. The brighter stars of galactic clusters are often brilliantly colored.

THE MOST FAMOUS GALACTIC CLUSTER—This photograph of the Pleiades cluster was taken with the 2.5 m (100 in.) telescope at Mount Wilson in California. The stars of this cluster are behind a luminous cloud of fine dust and gas that reflects and diffuses the stellar light.

A detailed study of the stars in the Pleiades cluster has shown that they are enclosed within a space about 30 light-years in diameter, and are about 300 light-years from the sun. The average distance separating stars in the cluster is about 3 light-years. Just as in the Hyades, the motion of the stars in the Pleiades can be observed. The velocity of stars observed in the direction of the Pleiades can be calculated, making it possible to say whether or not a star belongs to the cluster.

In spite of the fact that they have been studied for many years, the stars of the Pleiades cluster are still little known. Astronomers do know that the stars that have been identified as belonging to the cluster make up about half of those that presumably make up the total population of the cluster. However, the Pleiades cluster also contains dwarf stars having very weak luminosity and a mass inferior to that of the sun. Because of this weak luminosity, these stars are invisible to all but the most powerful telescopes.

About 500 open galactic clusters of the Pleiades type or of the more compact type, such as the one in Illustration 4, have been classified and studied. However, most are still unknown because they cannot be seen against a background thick with stars.

6

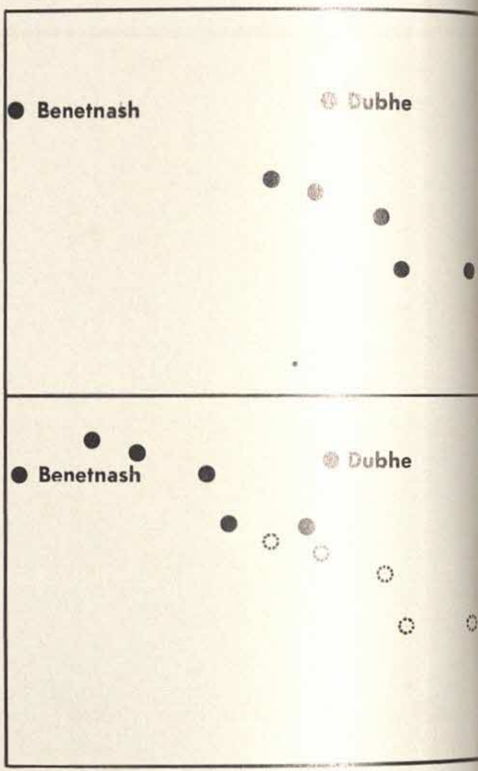
VISIBILITY OF NEARBY CLUSTERS—This photograph of an open galactic cluster in the constellation of Cancer was taken through a small telescope. Although this cluster, called the Praesepe for many centuries, is visible to the naked eye, its individual stars cannot be seen without a small pair of binoculars. The stars belonging to the cluster are those forming the most luminous group.

A study of a listing of known galactic clusters discloses that their estimated distances are in most cases small in comparison to the diameter of the Galaxy.

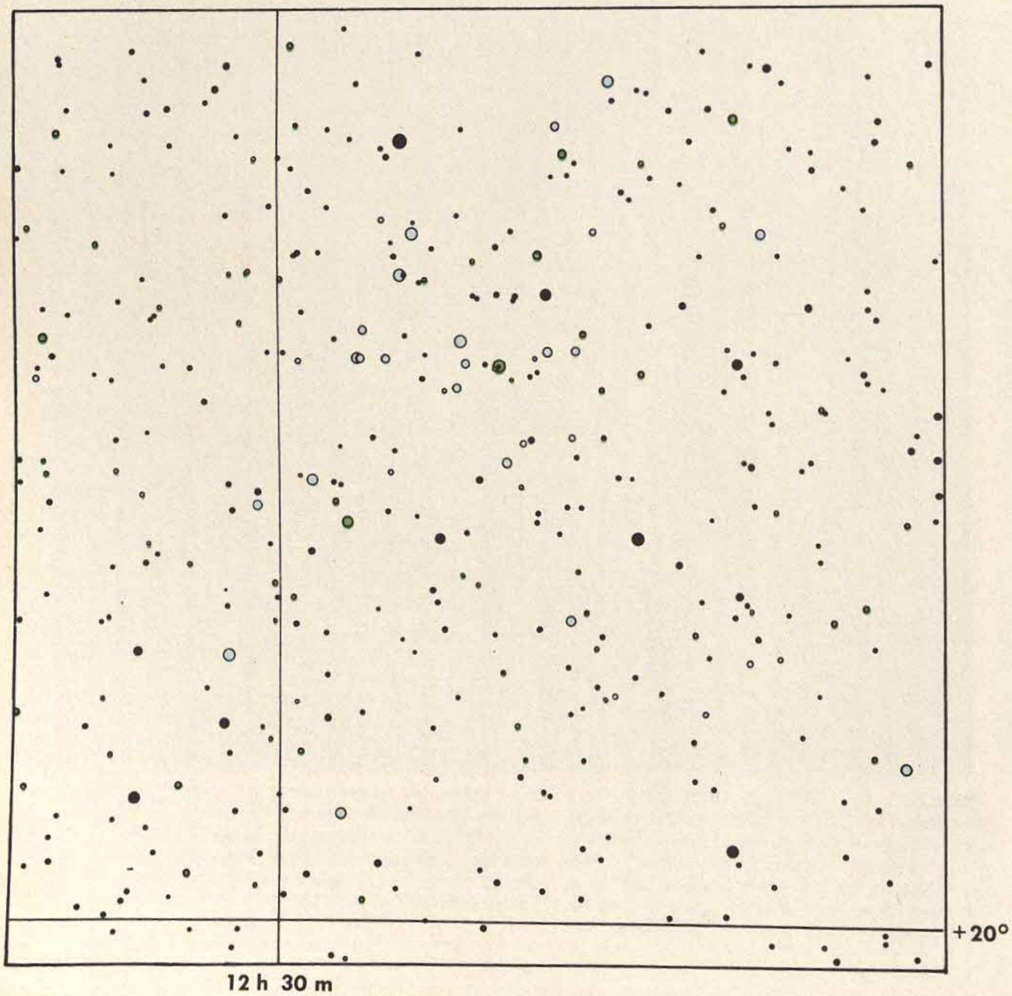
THE URSA MAJOR GROUP—These illustrations show the motion of the five central stars of Ursa Major over a period of 50,000 years. As can be seen, all of these five central stars have retained their reciprocal distances as they moved between Dubhe and Benetnash, which are outside the cluster. Dubhe now forms the lip of the so-called Big Dipper, while Benetnash forms the end of the handle.

Many other stars are connected with the five principal ones of Ursa Major. They are scattered haphazardly in space, forming an enormous galactic cluster with a diameter of more than 300 light-years. The solar system, the Hyades, the Pleiades, and the Coma Berenices cluster are inside this giant cluster.

7



8



THE COMA BERENICES CLUSTER—This map shows the stars in the constellation of Coma Berenices. Most stars on this map belong to a moving, compact, and united group forming a galactic cluster about 120 light-years distant from the solar system. This cluster and the Hyades cluster are extremely close to the sun. Others, like the Pleiades, the Praesepe, and the clusters of Perseus, are found at slightly greater distances. Other known galactic clusters are at still greater distances—several tens of thousands of light-years. Even these distances represent only a small fraction of the diameter of the Galaxy. The most distant galactic clusters known are found at a distance of 30,000 light-years from the solar system. The stars belonging to the Coma Berenices cluster are shown in colors indicating their spectral types. Only blue and green spectral types, corresponding to classes A and F, exist in large numbers.

THE SOLAR TOWER

the eye that follows the sun

The sun is a very special star, and very special instruments are needed to observe and photograph it. Because of the enormous quantity of heat and light that emanates from the sun, an ordinary telescope cannot be used to view it, for the light and heat would be concentrated by the objective in such a manner as to melt the focusing tube and the eyepiece. Instruments used to study the sun must have special characteristics.

Unlike the telescopes used to observe other celestial bodies, those used to observe the sun need not have objectives with large diameters, because the brilliance of the sun provides a bright enough image even with a small-diameter objective. Similarly, high resolution is not needed; even if the objective could resolve very sharp images, the image of the sun, seen through the turbulence of the Earth's atmosphere, would be unclear.

The chief instrument for solar observation is a large spectrograph, which, because of its size and weight, cannot be incorporated in an equatorially mounted telescope that can be pointed toward selected regions of the sky. A special device, the coelostat, is provided to meet the requirements for solar photography.

THE COELOSTAT

A spectrograph used to study the sun receives its light from various points on the image of the sun through a slit; the image is transmitted by an objective (lens or mirror). Although the spectrograph must remain in a fixed position, the image comes from a body—the sun—that moves across the sky. The problem is solved by using a pair of plane mirrors in a device called a coelostat. One of these mirrors is clock-driven to follow the sun's motion; as it turns it reflects the sun's image to the second mirror, which is fixed. The second mirror is so positioned that it, in turn, reflects the image it receives to the objective, which focuses the image through the slit of the spectrograph. Thus the coelostat makes it possible to observe a moving celestial body with a fixed telescope. One type of coelostat receives horizontal solar rays; a second type receives vertical solar rays.

THE SOLAR TOWER

The coelostat is mounted on the top of a tower, in a small dome. Inasmuch as the mirrors of the coelostat are not large—ranging in diameter from about 3 cm (about 1.25 in.) in the smallest instruments to about 152 cm (about 60 in.) in the huge installation at the Kitt Peak observatory in Arizona—a dome of a few yards in diameter is large enough to house the instrument. The image is directed vertically down the tower, through the objective, to a room at ground level. Here, observers study the bright image of the sun; they look for sunspots, faculae (bright spots on the sun's surface), and solar flares.

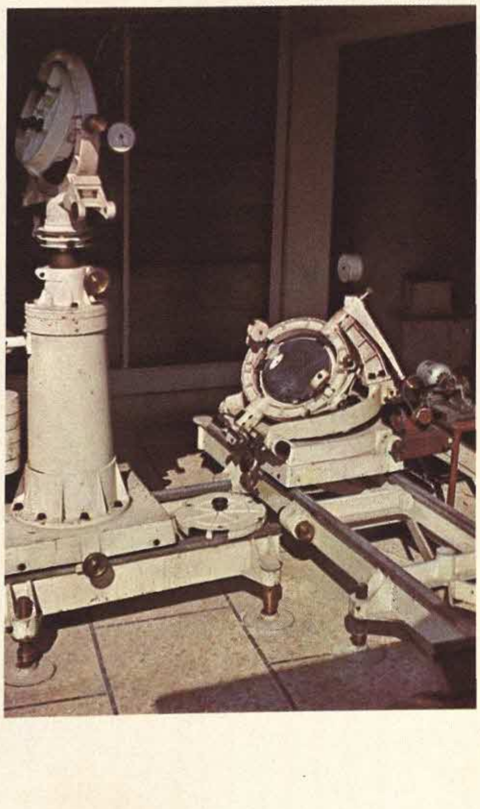
In a room on the ground floor is a shaft that communicates with a well, half as deep as the height of the tower and directly under the tower; the spectrograph is located in the well. When the spectrograph is to be used, the shaft, with its slit pointing downward, is uncovered. The image from the coelostat now passes through the slit to the spectrograph, which is made to concentrate as desired on a single feature of the surface shown in the image—a sunspot, for example.

THE SPECTROGRAPH

Because of the enormous quantity of light furnished by the sun, its image can be analyzed with very high dispersion, in contrast with the analysis of stars, in which the small quantity of light available allows for only minimal dispersion. Therefore, the sun makes possible a very long spectrum, with a distance of more

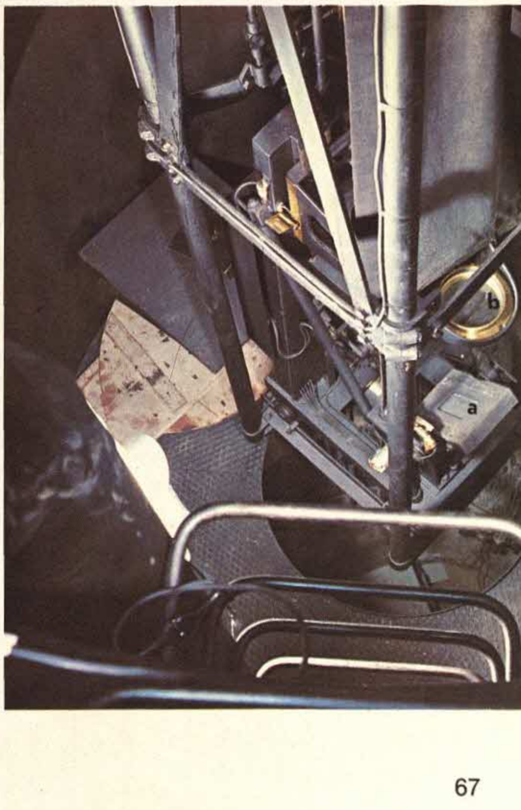
COELOSTAT—This coelostat is used with a horizontal telescope. The fixed mirror is at the upper left, and the moving mirror, driven by a clock, is on the right. A coelostat for a solar tower (i.e., a vertical telescope), similar in principle, is located in the dome of the tower.

1



THE WELL—At the bottom of the well is the diffraction grating **a,** which disperses the light. Above it is the collimator lens **b,** which focuses the light from the slit onto the grating below and collects the light from the grating, again forming the image.

2



3

A SOLAR TOWER—This solar tower is located at Monte Mario in Italy.

than 20 m (about 65 ft) between the red and the violet ends. An extremely long collimator is needed to obtain a spectrum of this length, and also a camera of extreme focal length; combined lengths of from 10 to 20 m (about 30 to 65 ft) are common in solar towers. Obviously, an impractically long instrument would result from the alignment of the camera directly with the collimator, and so an arrangement called autocollimation is used.

The collimator is comprised of the slit at the top of the well leading to the spectrograph and a lens and grating at the bottom of the well. The light that has passed through the slit and widened into a beam is collected by the collimator lens and directed onto the grating. All spectrographs used in solar towers employ a grating rather than a prism, because a grating produces greater dispersion and also has a considerably higher resolving power. The grating is arranged to reflect the rays from the collimator lens backward, in the same direction as the direction of incidence, but now dispersed; the dispersed rays again pass through the collimator and converge at the same distance from the slit. By tilting the grating a certain way, rays of a certain color can be directed back to the same slit through which they entered as part of a beam of undispersed light; a slightly different tilt of the grating throws the spectrum to the side of the slit. Thus an extensive portion of the spectrum can be photographed at the same time.

It might seem that the solar tower functions with no particular difficulty and requires no special care in its construction; but the opposite is the case. Stability is a prime requirement for the making of photographs and observations of the light of the sun, but the tower housing the telescope is slender, high, and vulnerable to the force of the wind. If the tower vibrates, the image of the sun under observation oscillates. To counteract this, most solar towers are housed in a double structure: an outer tower strong enough to resist winds; and an inner tower, independent of the outer tower, that houses the instruments.

Another source of difficulty is the great bulk of the spectrograph. Partly because of this bulk, it is located deep in the well, where the air may stratify in levels of different temperature; in winter, for example, cold air may enter from the outside, while the walls of the well, far underground, are relatively warm; thus, air of different temperatures circulates within the spectrograph and diminishes its resolving power. To prevent this, air at a constant temperature is forced into the well.

PHOTOGRAPHIC PLATES AND FILMS

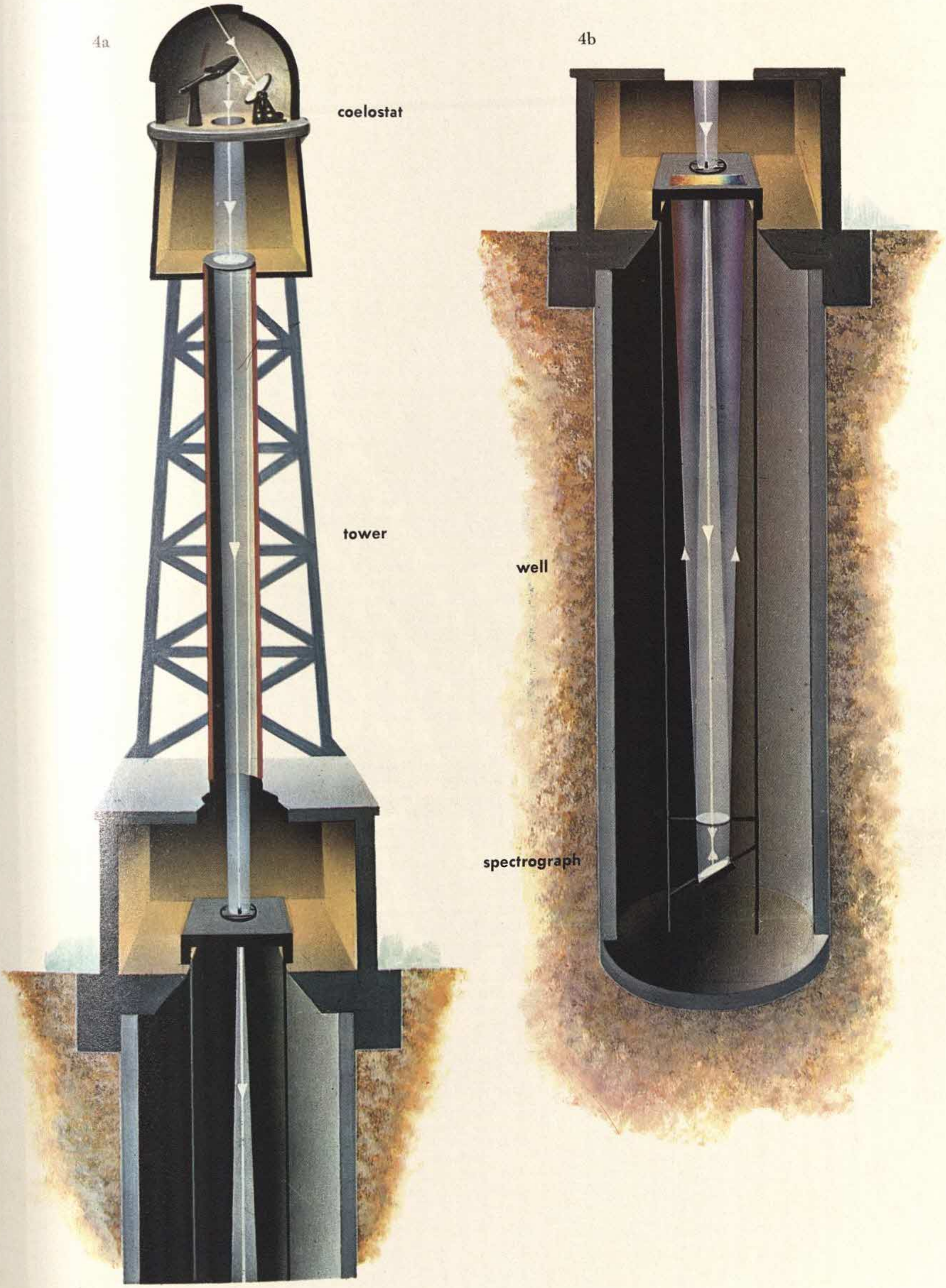
Astronomical plates and films are considerably more sensitive than commercially available materials; but because they fog more easily, they must be kept under refrigeration until shortly before use. There is a range of speeds available in astronomical plates; generally, the more sensitive a plate is to light, the grainier its structure is when developed and the poorer its resolution. When photographing the sun, however, fine-grain—and therefore relatively slow—plates can be used for the maximum resolution of fine detail on the sun's surface. Under these conditions, resolution is limited mainly by the Earth's unsteady atmosphere and by the deformation of the optics of the telescope caused by solar heating.

SOME ACHIEVEMENTS IN SOLAR PHOTOGRAPHY

In the early 1900s, the U.S. astronomer George Ellery Hale discovered that a considerable part of the daytime unsteadiness occurs near the ground as a result of the convection of heated air. He arranged, therefore, to have constructed the 60-ft and 150-ft (about 18-m and 46 m) solar towers at Mt. Wilson in California. Each has an objective lens of 30-cm (12-in.) aperture at the quoted distance above the focal plane. Subsequently, several other tower telescopes were built. The McMath-Hulbert observatory near Pontiac, Michigan, pioneered in making motion pictures of rapidly-changing solar phenomena.

In attempts to obtain solar photographs of even better resolution, balloons have been used to send telescopes to heights above nearly all the atmospheric unsteadiness. Results have been very good.

SECTIONAL VIEW OF A SOLAR TOWER—Illustration 4a shows the coelostat in the dome at the top of the solar tower. One of the mirrors of the coelostat is movable and follows the sun; the other mirror is fixed. The light from the coelostat passes down the vertical tube of the tower, through the slit at the room at ground level and down into the well to the spectrograph, where the light is dispersed and analyzed (Illustration 4b).



THE REFLECTING TELESCOPE

holding a mirror to the stars

The earliest telescopes had, as their principal component, a double convex lens with a spherical surface (called the objective) that refracted light rays inside a tube to form a focal image. When viewed through an ocular lens at the other end of the tube, the image was magnified. The process of refraction fails to focus rays of different colors at a single point, however, and thus produces iridescent halos that distort the image and interfere with the observation of small details. In the eighteenth century Isaac Newton, who discovered the true composition of light, devised a new kind of telescope—the reflecting telescope—in which the objective was not a glass lens, but a concave mirror of polished metal that produced an achromatic image (one without iridescent halos) that could also be magnified by an ocular lens.

The first large reflecting telescope—with a mirror 48 inches in diameter—was built in 1789 by the English astronomer William Herschel, who also improved the quality of the mirror; its surface was no longer spherical by this time but parabolic, eliminating another source of distortion. During this same period, however, the making of lenses was so advanced, correcting both the chromatic and spherical aberrations (distortions), that interest was renewed in refracting telescopes, especially because the mirrors of the reflecting telescopes were difficult to maintain at a peak of efficient operation. Chemical developments then resulted in a technique of coating a glass surface with a silver film to make a superior mirror, and the reflecting telescope returned to favor in the late nineteenth century. In the present century, silver was replaced by aluminum, and the most powerful telescopes—including the Hale telescope on Mount Palomar, with its 200-in. mirror—are all reflectors.

OBSERVATIONS MADE WITH TELESCOPES

Different kinds of telescopes are used to make different kinds of observations. One feature that may differ is the focal length of the apparatus—the distance between the center of the objective (lens or mirror) and the point where the rays of light converge to form an image. This point, called the focal plane, is where film is placed if the telescope is used to take photographs. Some telescopes are used expecially to take photographs of stars, which are points of light; in this case, and even in photographing planets, long focal length is desirable—a length five to ten times that of the mirror diameter. If nebulas, which are areas rather than points, are to be photographed, focal lengths of two to five times the mirror

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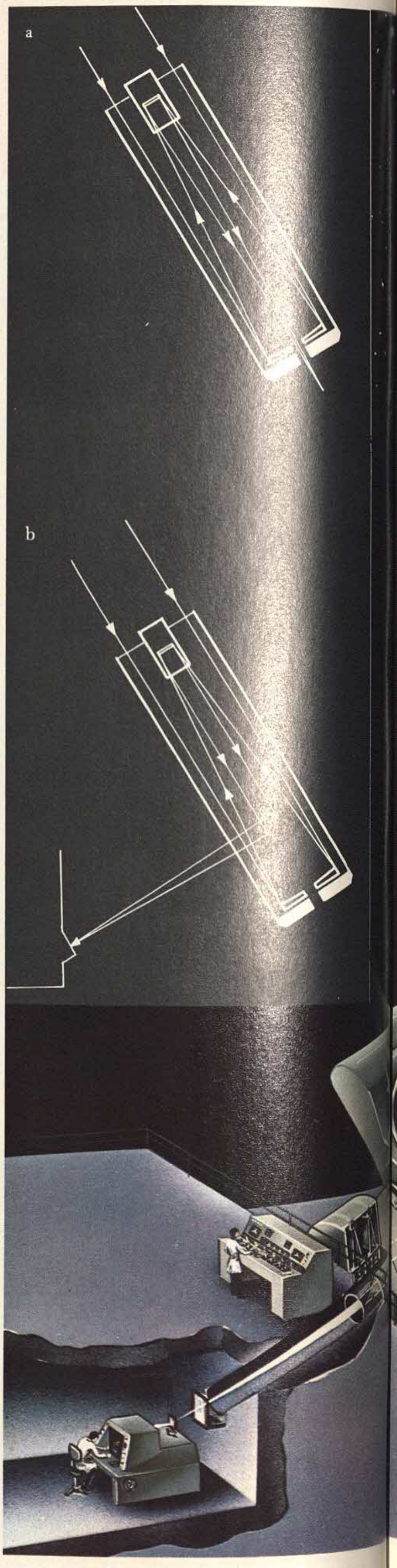
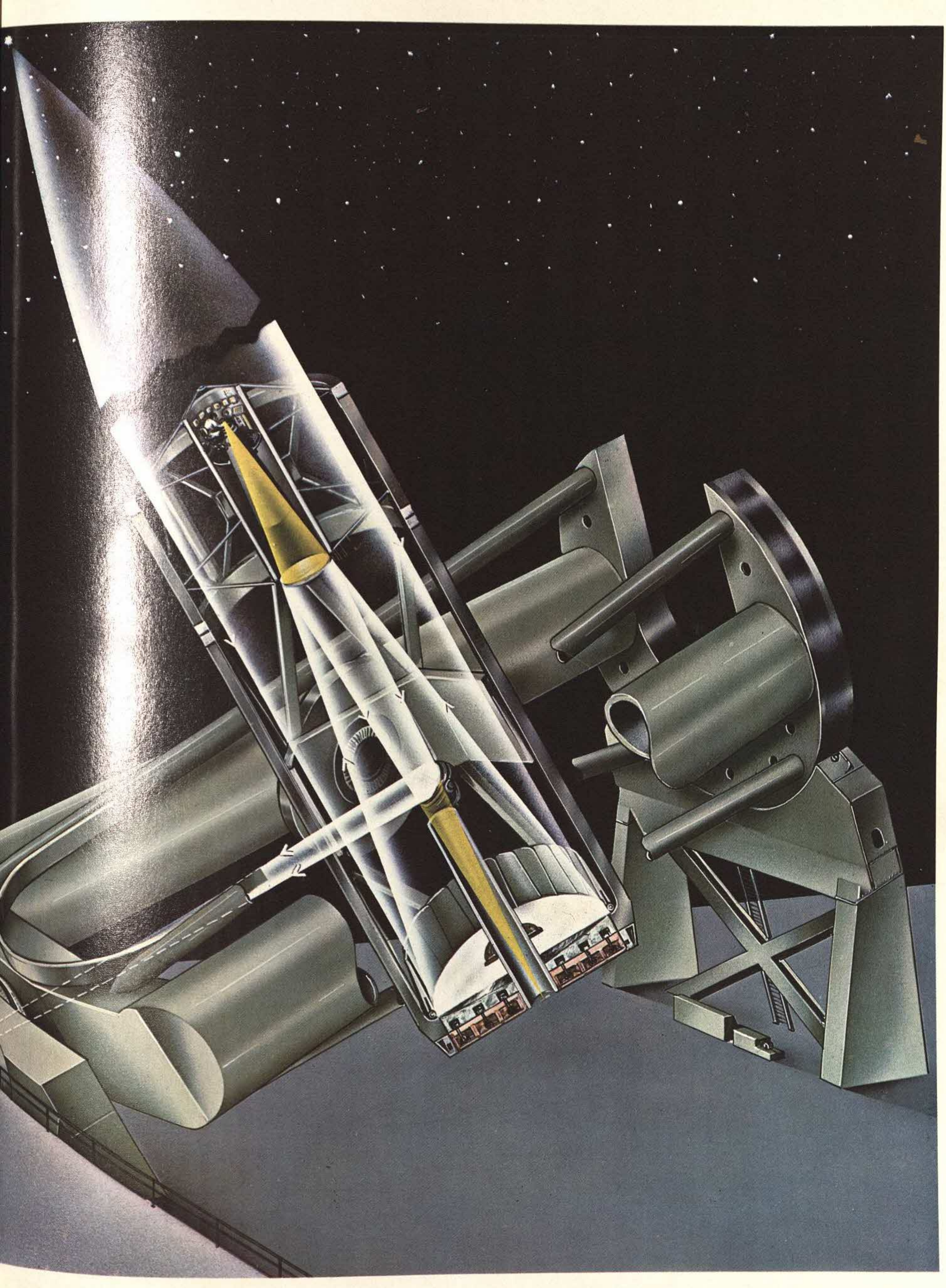


LENGTHENING OF THE FOCUS—This is a cross section of a large telescope, showing the arrangement of a complex set of mirrors by which the focal length may be increased and the image formed at the most convenient locations.

One way of increasing focal length is by allowing the light rays to be reflected twice down the full length of the telescope. After traveling to the parabolic mirror at one end, the rays are reflected back to a hyperbolic convex mirror at the other end, and thence back through a hole in the parabolic mirror, where the focus is achieved. This increases magnification, although some intensity is sacrificed. Such an arrangement **a** is known as the Cassegrain focus.

A further extension is possible, with a mirror of very great focal length, by intercepting the beam as it returns from the hyperbolic mirror with a plane mirror set at an angle of 45°; this mirror diverts the beam through a hole in the side of the telescope to a more convenient location for the eventual focus. Such an arrangement **b** is known as a coudé focus, from the French word *coude* for "elbow." An additional advantage of the coudé focus is that it is independent of the movement of the telescope as it follows the motion of the sky. This fixed position makes it possible to station at the point of focus a camera, a photometer, or a spectrograph of great weight—perhaps several tons—that would not easily be accommodated by the already overburdened telescope.

Small telescopes are usually equipped with a plane mirror set at an angle of 45° in front of the objective, which also deflects the beam to a convenient location outside the tube of the telescope. In this way instruments used to observe the image can be located outside the tube, without obstructing it. In larger telescopes, on the other hand, excepting those equipped with coudé focus, the instruments are mounted along the axis of the tube, and may be placed, along with the astronomer, in a cabin of adequate size for comfortable observation.



diameter are desired. If a photometer or a spectrograph is used, other focal ratios may be needed. Large telescopes are expensive and difficult to build; therefore, they are designed to be used for as many purposes as possible. Some may incorporate a variety of focal lengths in the same instrument.

DIFFERENT TYPES OF MOUNTINGS

A mounting commonly used for telescopes is called "equatorial" because it reproduces the rotation of the celestial sphere. Although several designs of equatorial mountings are used, the basic problem is to mount the apparatus so that it will follow the motion of the entire sky; otherwise, the zone under observation would disappear from the field of view. The mirror alone may weigh more than 10 tons. Neither the mirror nor its massive mounting can be out of alignment by more than a few thousandths of a millimeter. The construction of these mountings is an amazing feat of engineering.

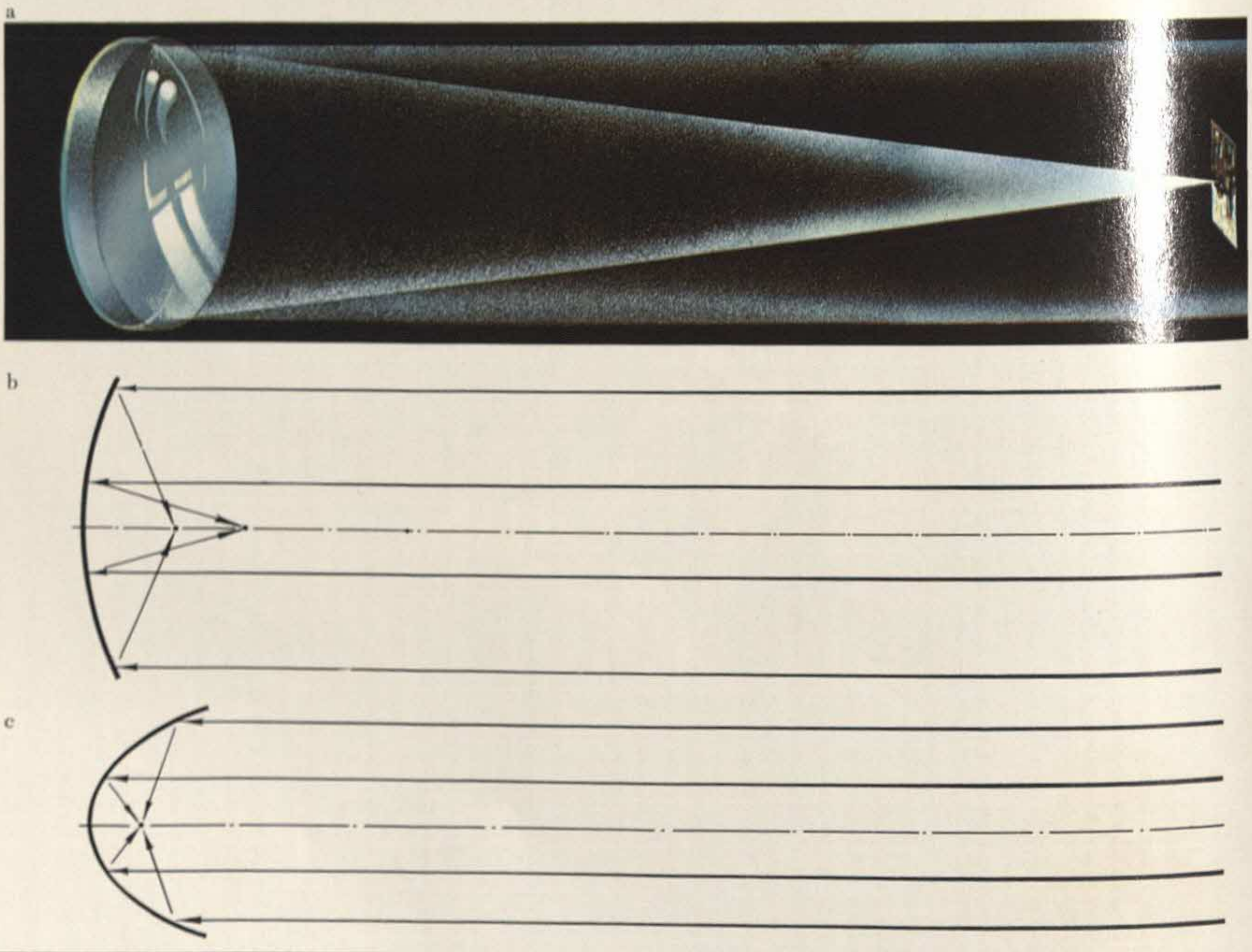
The perfectly regular movement of the telescope is supplied by a motor. A system of multiple gears reduces the speed of rotation of the motor from many revolutions per second to one revolution per sidereal day, enough to follow the motion of the sky.

With such extremely high reduction and the perfect balance of the apparatus, a huge telescope such as the Hale, with a mounting weighing about 450 tons, can track a celestial zone when driven by a motor of about 0.1 hp. The necessary stability is obtained by heavy, squat construction and by the use of counterweights to relieve the strain on the heaviest parts of the mounting.

2

HOW THE IMAGE IS FORMED—A telescopic mirror with a spherical surface is shown in Illustration 2a. The radius of curvature—the radius of the entire sphere of which the mirror would comprise a segment—is about 100 times the length of its diameter (for example, a diameter of 4 in. and a radius of 400 in.). The light rays coming from an object at infinity, or at least at a very great distance, are reflected by the mirror to form a real inverted image. This image is formed at the focal point; that is, along the axis of the mirror at a distance equal to half the radius of curvature (the focal length of the mirror).

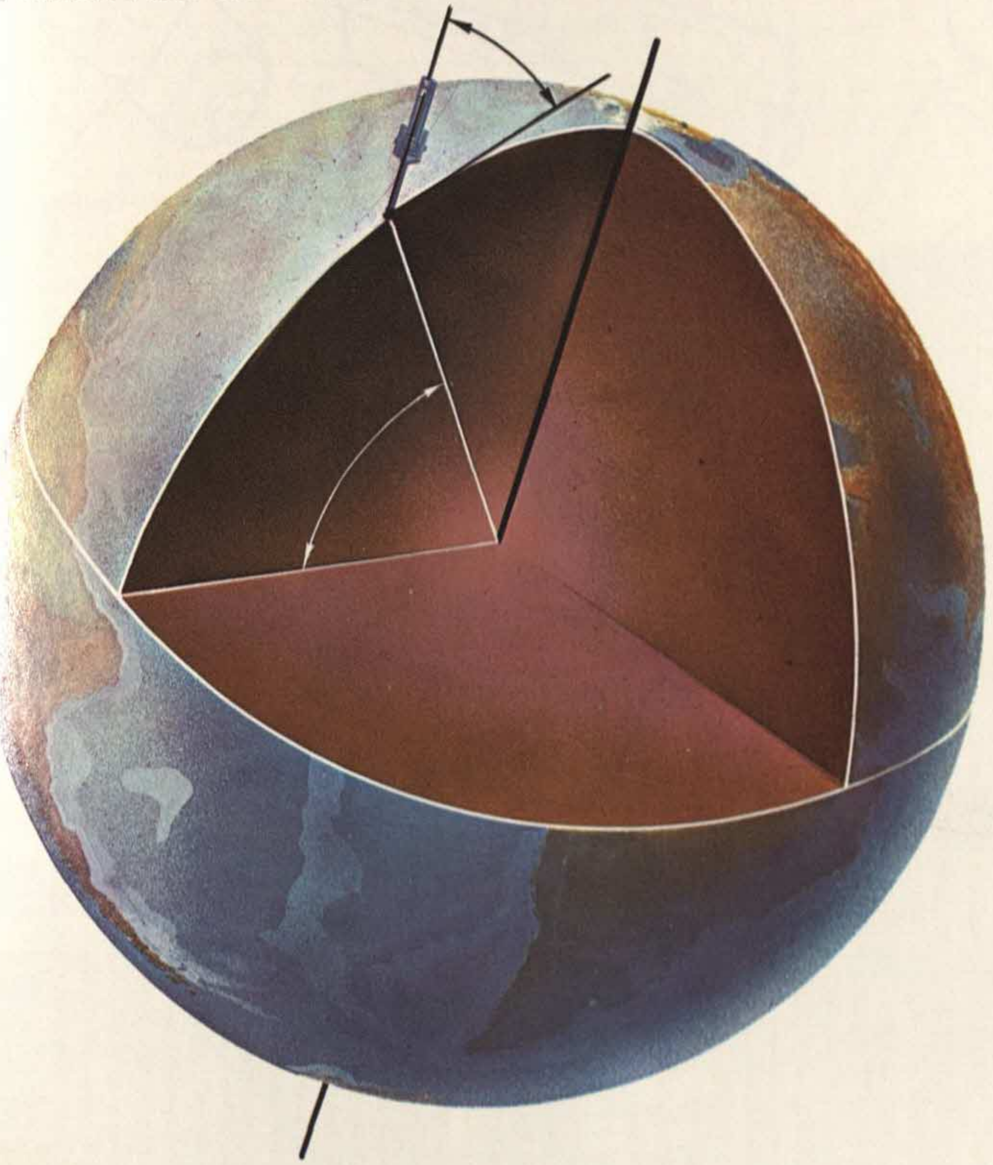
Illustration 2b shows the light rays approaching from the right and striking the surface of a spherical mirror. Inasmuch as the rays come from infinity, or a very long distance, they are parallel; those that strike the mirror near its center are reflected back to the focal point, while those that strike the mirror further from the center are reflected to a point along the axis between the focal point and the center of the mirror. This explains why a spherical mirror cannot be used in astronomical telescopes (unless the focal length is very much longer than the diameter of the mirror); in such a case the image would not be sharply reflected on a single focal plane. However, if a parabolic mirror (Illustration 2c) is used, the rays coming from an infinitely distant object are reflected at a single point, and a sharp image is formed.



THE EQUATORIAL MOUNTING—If a telescope were fixed in any direction (except toward the pole), the stars would seem to move rapidly across the field of vision and pass from view, because of the apparent motion of the sky—which is actually caused (like the apparent motion of the Sun) by the rotation of the Earth. Both for ordinary viewing and especially for photographing the stars and their spectra, a telescope must be able to keep a selected region of the sky in its field of vision—otherwise the photograph of a star, for example, would appear as a line rather than as a point. Inasmuch as the rotation of the Earth causes the apparent motion, this can be counteracted by rotating the telescope itself in exactly the opposite direction and at the same speed.

This is accomplished by careful design of the mounting, so that the axis of rotation is constantly and precisely parallel to that of the Earth. This polar axis is, therefore, constructed to point, like the Earth's axis, toward the Pole Star. The polar axis supports a second axis, set perpendicular to the polar axis and capable of turning from north to south at a variable angle called the angle of declination. The telescope is mounted on this declination axis, and can be moved on its two axes to point at any region of the sky. Once it is fixed on a selected region, the clockwise rotation of the polar axis, at the rate of one revolution in 24 hours, enables it to follow the motion of the stars in that celestial region.

3



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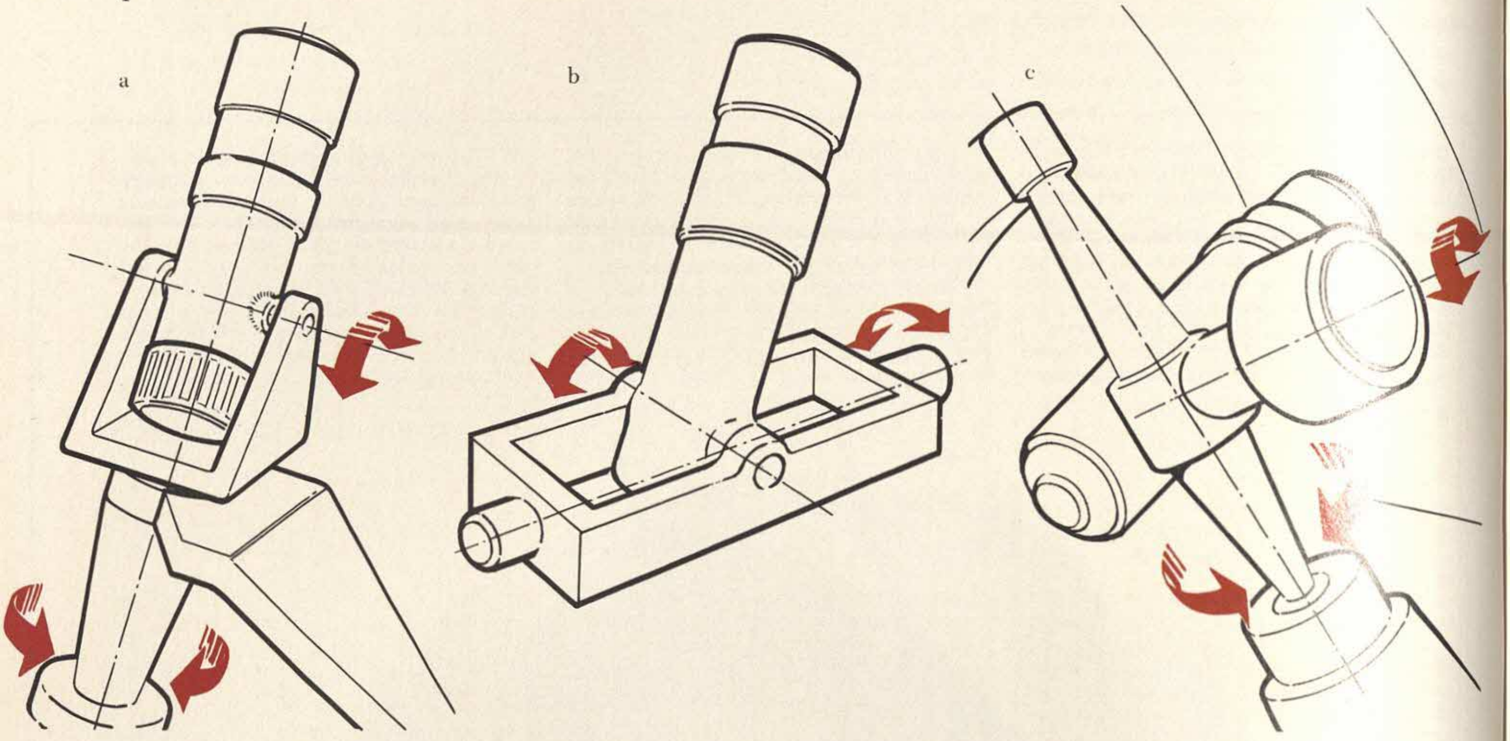


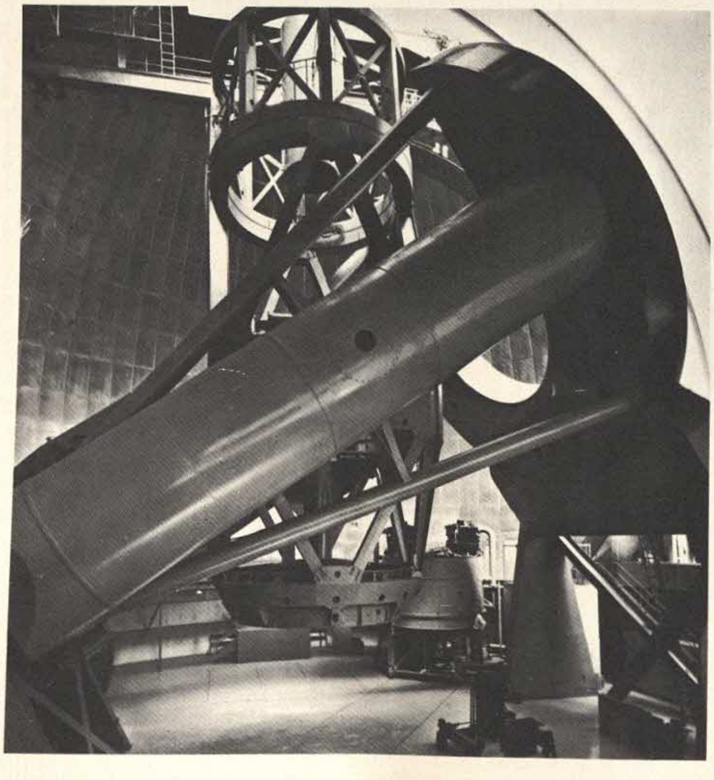
TYPES OF MOUNTINGS FOR REFLECTORS—Illustration 4a shows a yoke mounting. At one end of the polar axis is a yoke holding the support bearings for the declination axis. The telescope turns within the yoke when it is pointed toward the pole. The largest yoke mounting constructed supports the 120-in. telescope on Mount Hamilton.

Illustration 4b shows a cradle mounting. The polar axis is divided in two and supported at its ends. Between the two shafts into which it is divided, the telescope is supported on ball bearings that permit it to move through the angles of declination. This type of mounting is used for the 100-in. telescope on Mount Wilson and the 200-in. telescope on Mount Palomar; in the latter, the cradle is open at the north end so that the viewer can point the telescope directly at the pole.

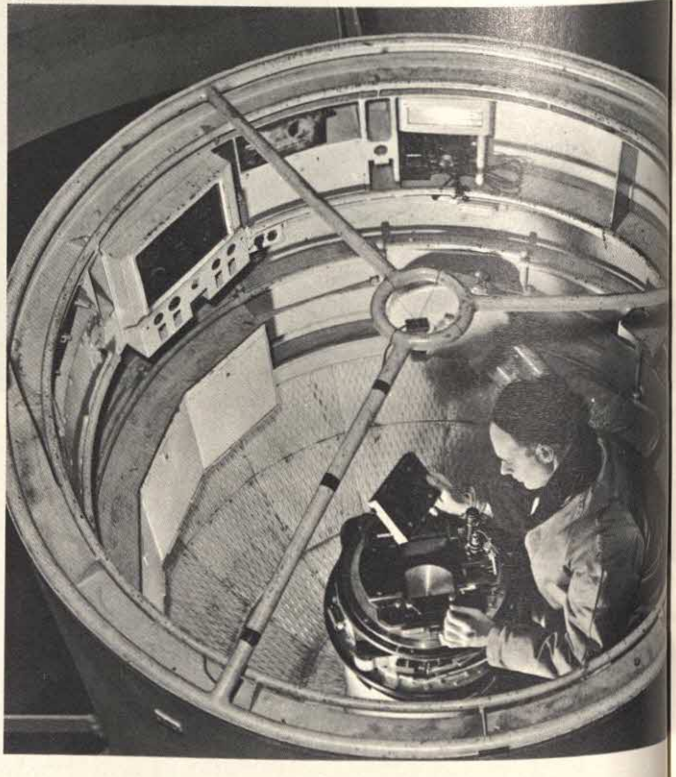
An English mounting is shown in illustration 4c. The declination axis is mounted at the upper end of the polar axis. The telescope is mounted at one end of the declination axis and a counterweight is mounted at the other end. This mounting must be raised on a pier, so that the telescope will not touch the floor.

THE HALE TELESCOPE ON MOUNT PALOMAR—This is the largest telescope in the world, and was completed in 1950; 20 years, from 1928 to 1948, were required to prepare the mirror alone. The moving part weighs more than 400 tons, but the mounting is so perfect that neither distortion nor vibration occurs during its operation. Within the yoke support **f** is room for a man. On the right is shown an astronomer at the top of the telescope preparing the instruments for observing and photographing the image at the main focus. He can move about in the cabin, even while exposures are being made, without disturbing or distorting the photographs.

5a



5b



THE SCHMIDT TELESCOPE | charting the skies

Astronomers attempting to map the entire sky are faced with a problem: the field that must be covered on their photographic plates involves some 40,000 square degrees, whereas the most suitable telescopes, used as cameras, produce plates covering a field of less than 1 square degree.

An ordinary camera takes photographs covering about 30 degrees on each side, or about 900 square degrees; it could photograph the entire sky in only 45 exposures, if these were properly juxtaposed. However, this kind of camera does not have the light-gathering power to take the pictures needed. On the other hand, a reflecting telescope with a parabolic mirror is especially suited for photographing the sky, because the light is gathered by a large mirror and focused sharply on the photographic plate at the prime focus. The extremely limited field of view, however, would require that almost a half-million photographs be taken to chart the entire sky. Each photograph would require an hour of exposure, or about 10 per night; and only about 200 nights per year are suitable for celestial photography. Therefore, about 200 years would be required for a telescope of this kind to carry out the task.

A parabolic mirror is particularly efficient, because only 10 percent of the incident light is lost if the mirror is coated with aluminum. On the other hand, in the objective lens of a refracting telescope, much more light is lost because each reflecting surface of the lens reflects about 4 percent of the incident light. If the lens has three elements, with six reflecting surfaces, at least 20 percent of the light is lost. Although it is possible to make low-reflection lenses by coating them with special materials, the process always slightly changes the color of the light that passes through the lens. In taking astrophotographs, it is very important that the light falling on the plate not be altered to the slightest degree, even though the picture is taken in black and white; therefore, coated lenses are usually not used in astronomical instruments.

CHARTING THE SKY

A large parabolic mirror, which takes such excellent pictures of a small celestial area, would be comparatively ineffective if it were not possible to chart the entire sky with a less powerful camera having a greater field of view. Toward the end of the nineteenth century, large refracting objective lenses were built to accomplish this task; however, these lenses were so large, so thick, and composed of so many elements to gather enough light, that most of the light gathered was also absorbed before it could be photographed. The Russian-German optician Bernhard Schmidt, of the Hamburg observatory, devised a new kind of optical system in 1930 to provide wide-angle photographs for astronomical use. It was essentially an adaptation of the reflecting telescope, with its mirror—much larger than any effective lens—to gather the light. Instead of using the parabolic mirror, which has the advantage of converging parallel rays to a single focus, Schmidt decided to use a spherical mirror (because such a mirror gives a larger field of view), and to eliminate spherical aberration—which somewhat scatters the incident light rays, blurring the focus—by inter-

THE 48-IN. SCHMIDT TELESCOPE—At first Schmidt built small telescopic cameras, but later astronomers made use of larger Schmidt instruments. This photograph shows the largest Schmidt telescope-camera built; it is located at the Mount Palomar observatory and has a 48-in. spherical mirror. The observatory at Potsdam, Germany, has a telescope that, by exchanging lenses, can be modified into a still larger Schmidt telescope having an 80-in. spherical mirror. This telescope, however, is not exclusively used for astrophotography.

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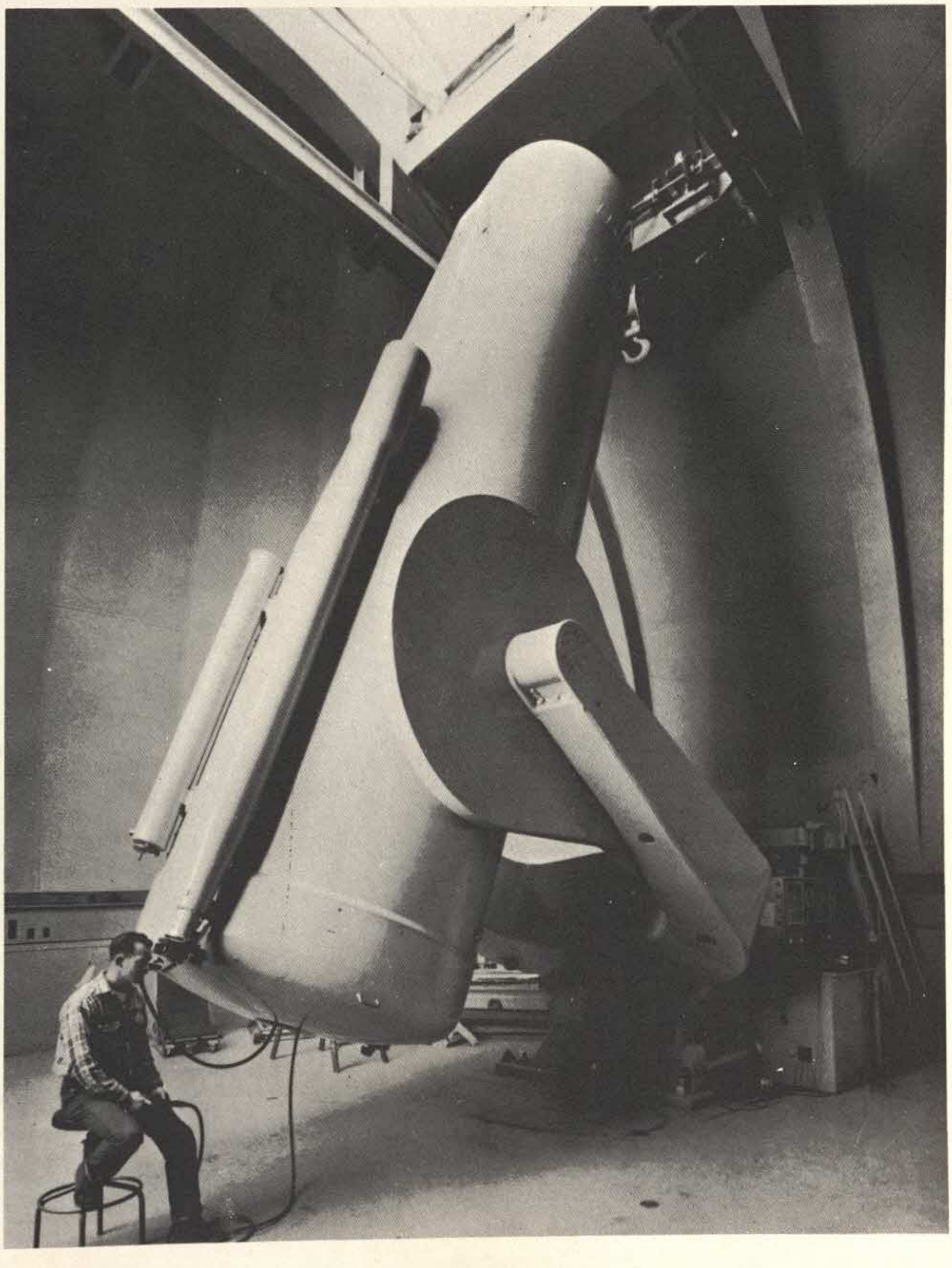
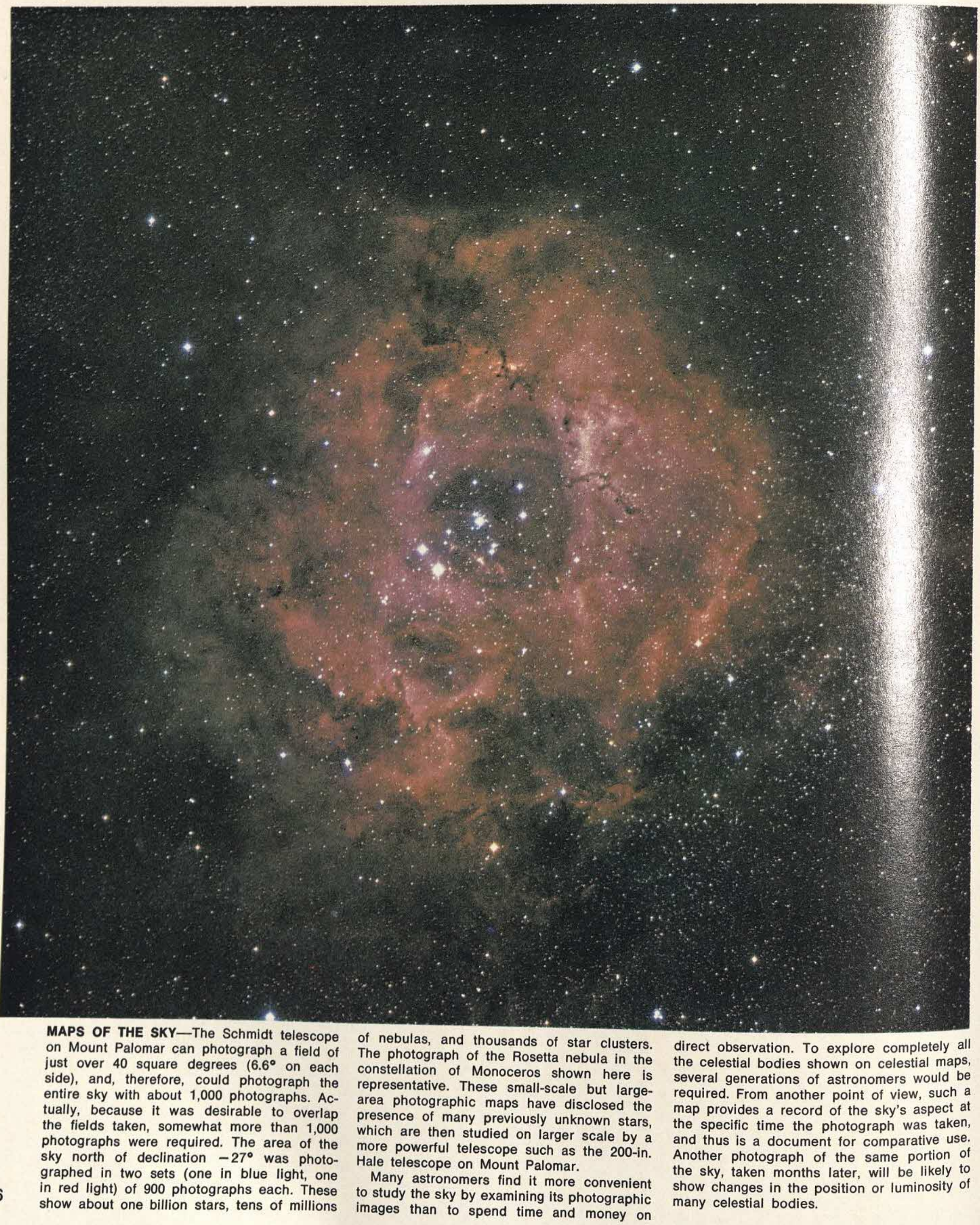


posing a corrective lens of special configuration. This lens intercepts the parallel rays before they reach the spherical mirror and causes them to fall on the mirror at angles that result in a focus just as perfect as that provided by the parabolic mirror, but with a much shorter focal length and a wider field of view.

2



MAPS OF THE SKY—The Schmidt telescope on Mount Palomar can photograph a field of just over 40 square degrees (6.6° on each side), and, therefore, could photograph the entire sky with about 1,000 photographs. Actually, because it was desirable to overlap the fields taken, somewhat more than 1,000 photographs were required. The area of the sky north of declination −27° was photographed in two sets (one in blue light, one in red light) of 900 photographs each. These show about one billion stars, tens of millions of nebulas, and thousands of star clusters. The photograph of the Rosetta nebula in the constellation of Monoceros shown here is representative. These small-scale but large-area photographic maps have disclosed the presence of many previously unknown stars, which are then studied on larger scale by a more powerful telescope such as the 200-in. Hale telescope on Mount Palomar.

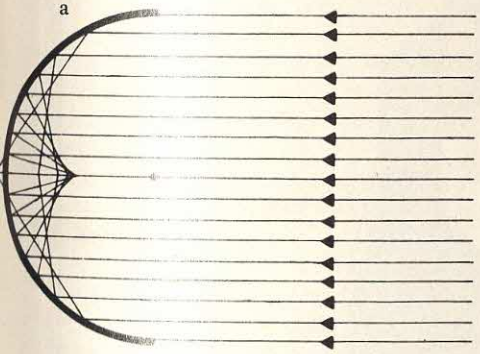
Many astronomers find it more convenient to study the sky by examining its photographic images than to spend time and money on direct observation. To explore completely all the celestial bodies shown on celestial maps, several generations of astronomers would be required. From another point of view, such a map provides a record of the sky's aspect at the specific time the photograph was taken, and thus is a document for comparative use. Another photograph of the same portion of the sky, taken months later, will be likely to show changes in the position or luminosity of many celestial bodies.

3

DIAGRAM OF THE SCHMIDT TELESCOPE—In Illustration 3a, light beams of parallel rays (such as those coming from a star) strike the spherical mirror and are reflected to a focus dispersed between various distances, along the mirror axis, from the center of the mirror. The rays striking near the axis are reflected back to converge at a point furthest from the center (that is, the point with the longest focal length); those striking the mirror near to its edge are converged along the axis at a point nearer the center (that is, the point with the shortest focal length). If a photographic plate is placed at the plane of the longest focus, the image of the star appears as a small point surrounded by a halo—the usual effect of spherical aberration.

To eliminate this aberration, Schmidt interposed a lens (Illustration 3b) with a specially figured surface that would cause the light passing through it to converge over the area where the mirror is least convergent and to diverge over the area where the mirror is most convergent—in other words, to compensate for the spherical mirror—so that the rays, in reflecting, would focus in a sphere with a radius equal to half that of the spherical mirror. This means that the photographic plate must itself be mounted on a convex surface. If the curvature is not too pronounced, however, the plate can be mounted on a mold so that, when pressed down, it takes a spherical shape.

a



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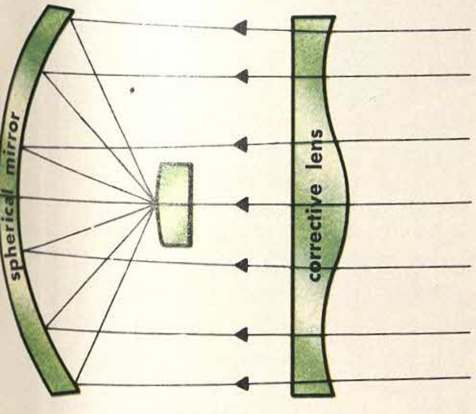

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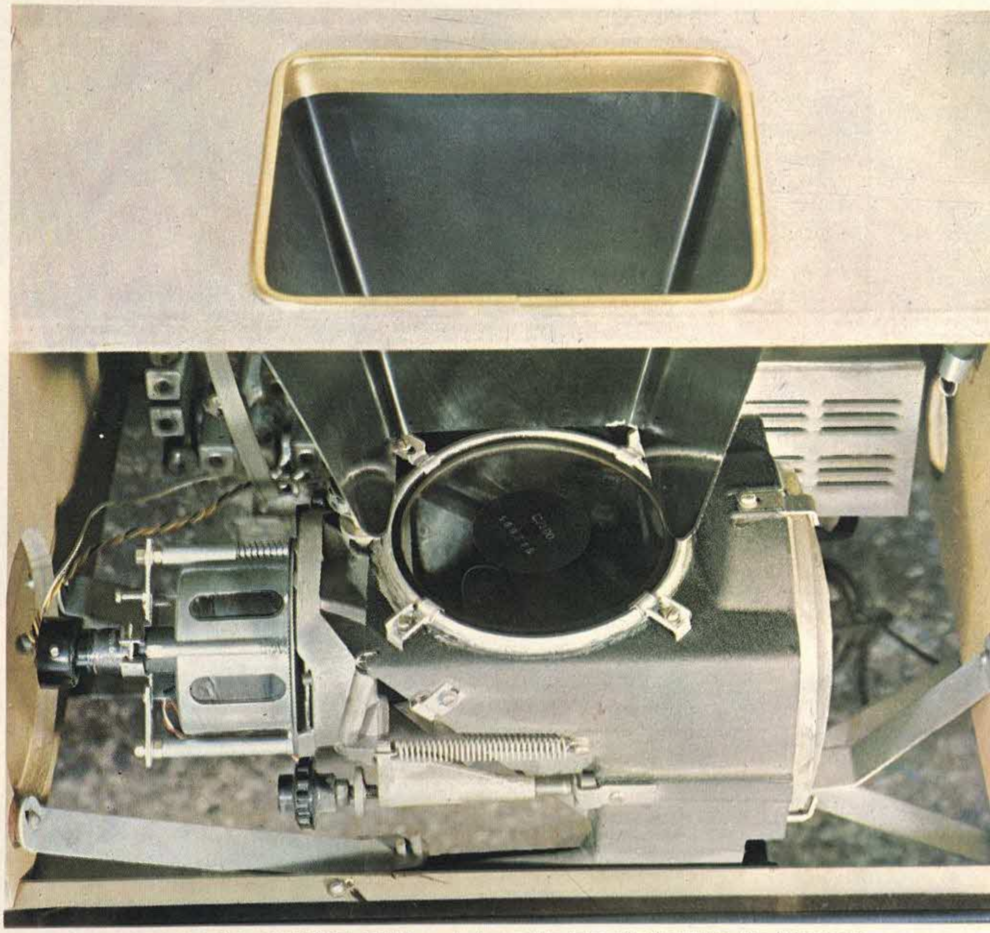
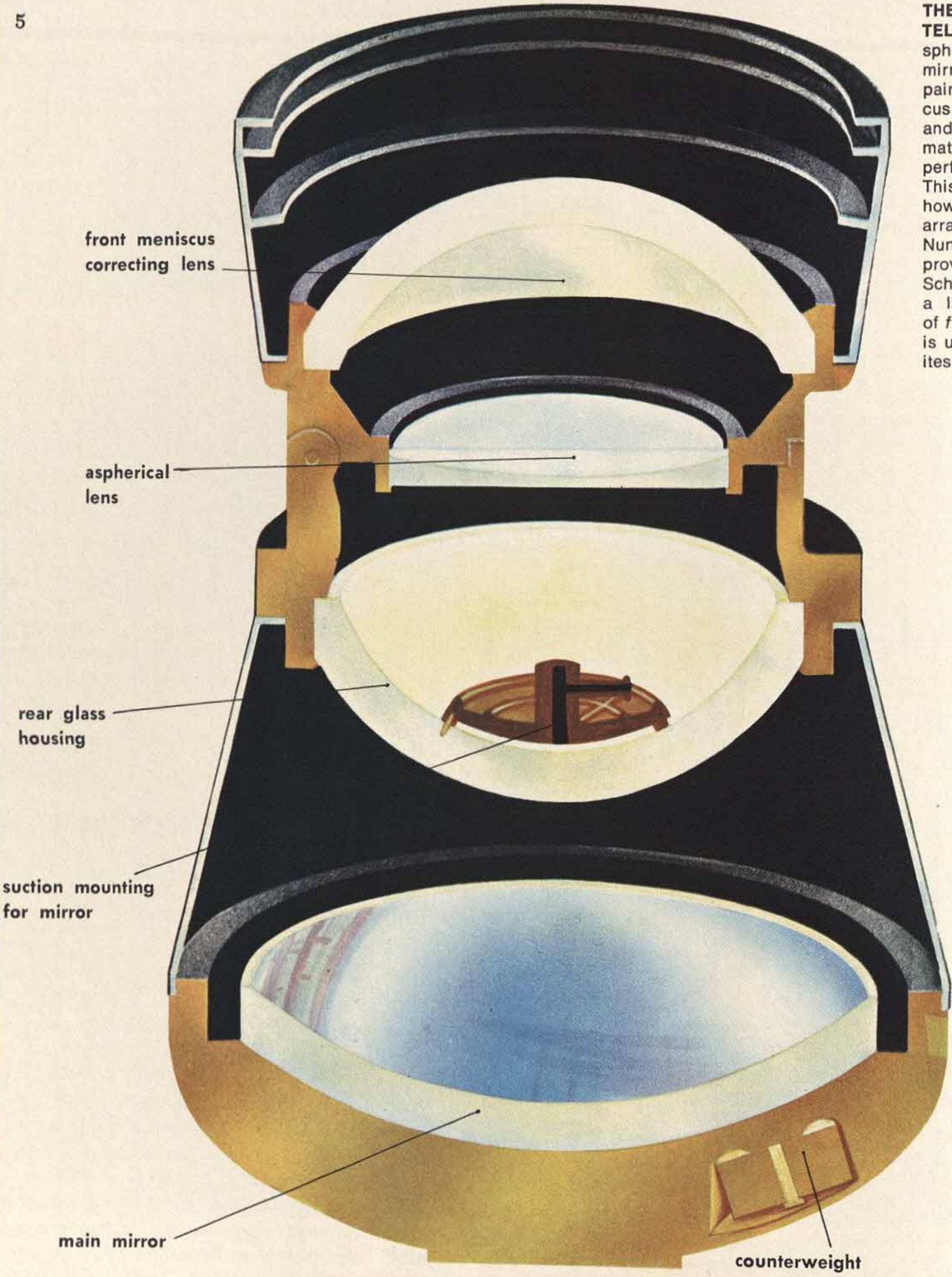


APPLICATIONS OF THE SCHMIDT TELESCOPE—Although the most important application of the Schmidt telescope is in astronomy, this optical invention has many other uses. With improved characteristics, Schmidt telescopes have been built to track man-made satellites and meteorites. The optical system may have a light-gathering power of *f*/0.65 (the ratio between the diameter of the corrective lens and the focal length of the camera—a power equaling that of the fastest photographic lenses); therefore, the telescope can be used to collect infrared radiation (which may be absorbed by slower lenses). The telescope may also be adapted to other apparatuses requiring objectives of the highest speed. Moreover, the telescope may be used as a projection lens rather than as a lens to gather light. Such a system is used, for example, in high-power lighthouses and electric lanterns. Finally, it can be used to project television images, as shown in the illustration.

THE INVENTOR

Schmidt (1879–1935), whose invention was an outstanding achievement in astronomical optics, lost an arm in early childhood; nevertheless, he taught himself to grind lenses and to make his own optical instruments. He studied engineering at Göteborg, Sweden, in 1900 and 1901, and he continued his technical education at the Institute of Mittweida, Germany, from 1901 to 1904. Schmidt lived and worked at Mittweida most of his life, manufacturing lenses and mirrors for telescopes and other optical instruments. He obtained several patents. The parabolic mirrors that he made during this period and his 16-in. horizontal telescope of 1909 established his reputation. In 1926 Schmidt joined the staff of the Hamburg observatory at Bergedorf, Germany; during the far eastern solar eclipse expedition of 1929, he conceived the idea of a mirror system that would eliminate spherical aberration. The first 14-in. Schmidt telescope was begun at Bergedorf in 1930 and was completed in 1932, three years before his death.

5



THE SUPER-SCHMIDT TELESCOPE — If the spherical aberration of a mirror is corrected by a pair of lenses—a meniscus (crescent-shaped) and an aspherical achromatic lens—exceptional performance may result. This illustration shows how the optical parts are arranged in the Baker-Nunn telescope, an improvement on the Schmidt telescope. With a light-gathering power of *f*/0.65, this instrument is used to study meteorites and satellites.

THE TRANSIT INSTRUMENT | a tool for practical astronomy

According to a story, an astronomer was asked many years ago in what respect his science was useful. He replied that, without astronomy, there would be no coffee for him to drink. The reply is not as absurd as it may have seemed, for most of the world's coffee is drunk by persons who live where coffee plants do not grow. The coffee must be transported generally by sea; and in order to navigate the seas, a course must be set. The most reliable method of setting a course at sea is based on a knowledge of astronomy—particularly the positions of the stars in relation to the ship.

The movement of the stars in relation to the solar system is very slow, and except for the apparent motion caused by the diurnal and seasonal movement of the Earth within the solar system, the stars may be considered fixed. Once their positions have been determined, they remain nearly the same over periods of centuries, and so have been useful to navigators.

PLOTTING THE POSITION OF A STAR

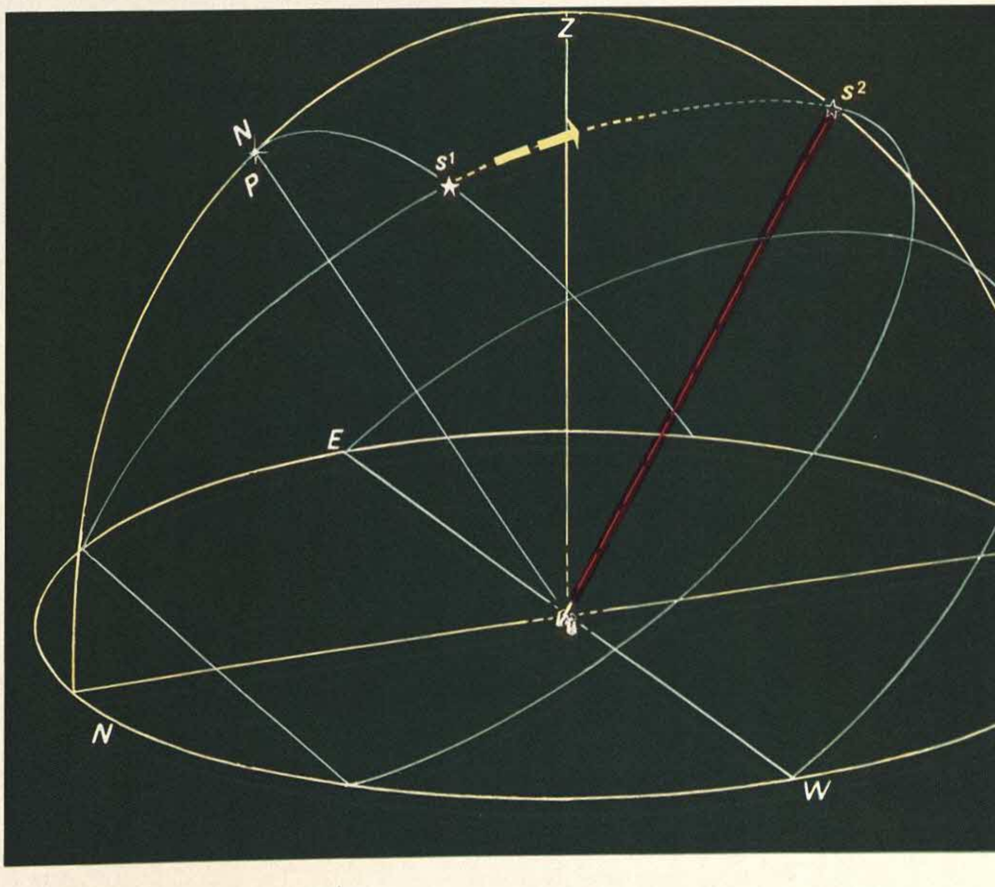
To plot the position of a star, a system of coordinates for the entire sky must be established within which this position may be located. The most practical framework is that of the celestial sphere, with the Earth in its center; an observer on the surface of the Earth therefore sees (weather permitting) half that sphere as the inside of a dome. Because of the Earth's rotation each day, the celestial sphere—with its many constellations of stars—appears to rotate in the opposite direction.

One point of reference is the celestial pole. Just as the Earth rotates around its axis (an imaginary line running through the center of the Earth, with a pole at the surface at each end), so the celestial sphere appears to rotate around an axis (an imaginary extension of the Earth's axis) with a pole at each end. One of these poles is that point in the sky around which the rotation seems to take place to the observer. (The North Star very nearly marks the location of the north celestial pole.) If the observer is at the Earth's North or South Pole, the celestial pole will appear to be directly overhead (at the zenith). If the observer is on the Earth's equator, the celestial pole will be on the north or south horizon. At any latitude between, the celestial pole is at an intermediate position between the zenith and the North or South Pole, and at an angle from that pole equal to the latitude of the observer. An imaginary line across the sky from the north horizon, through the zenith, to the south horizon (intersecting a celestial pole) is called the meridian. A great circle perpendicular to the meridian and at an angle of 90° from the celestial poles is called the celestial equator, and is an extension of the plane of the Earth's equator. The rest of the celestial sphere is sectioned by parallels to the celestial equator, corresponding to latitudes on the Earth's surface, and by lines from celestial pole to pole, corresponding to longitudes on the Earth's surface. These are the coordinates by which the positions of stars are plotted.

When the apparent motion of the sky causes a star to cross the meridian, it is important for practical astronomy to observe the precise time of passage, or transit. This position is especially useful

THE TRANSIT OF A STAR—This illustration shows the passage of a star over the meridian, and how to observe it. The circle **NWSE** represents the horizon around the location of the transit instrument, shown in the center of the circle. The semicircle **NZS** represents the meridian, along which the telescope can be pointed (with **Z** as the zenith); **P** locates the celestial pole, and all the stars (except the circumpolar stars) pass once each day across the arc **PZS.** The star originally located as **S¹** travels along the dotted section of the traced arc until it intersects the meridian at **S².** The instant of time at which this occurs is registered; at the same time, the arc **Ps²** is measured and its angle computed.

1



because a star in transit at its highest position above the horizon can be observed with least distortion in this position, where atmospheric refraction, or the occlusion of atmospheric dust, is at a minimum. Two measurements are taken: the precise instant in time of the transit; and the altitude above the horizon at that instant, measured in degrees and fractions of a degree (minutes and seconds) of arc.

THE TRANSIT INSTRUMENT

To measure the instant of a star's passage across the meridian, a device called a transit instrument is used. It is a small refracting telescope with an objective lens about 10 cm (about 4 in.) in diameter, mounted on a horizontal rotary axis with a precise east-west alignment. The instrument, with its axis perpendicular to the axis of the mounting, can swing only along the line of the meridian. The mounting must be both precise and very simple.

Inasmuch as the purpose of the transit instrument is to determine precisely the instant when a star crosses the meridian, its capacity to measure also the altitude of the star at that time is not of the utmost importance. However, the instrument must not be pointed to either side of the meridian at the time of passage. To avoid this possibility, the supports for the horizontal axis are two identical V-shaped and perfectly aligned blocks of hardened bronze. A series of star fixes are taken with the telescope set on these supports; then the telescope is raised and turned around, and set back on the supports facing the opposite direction. Now the same stars are fixed again, and the passage across the meridian is again timed. A comparison of the timings indicates the accuracy of the instrument.

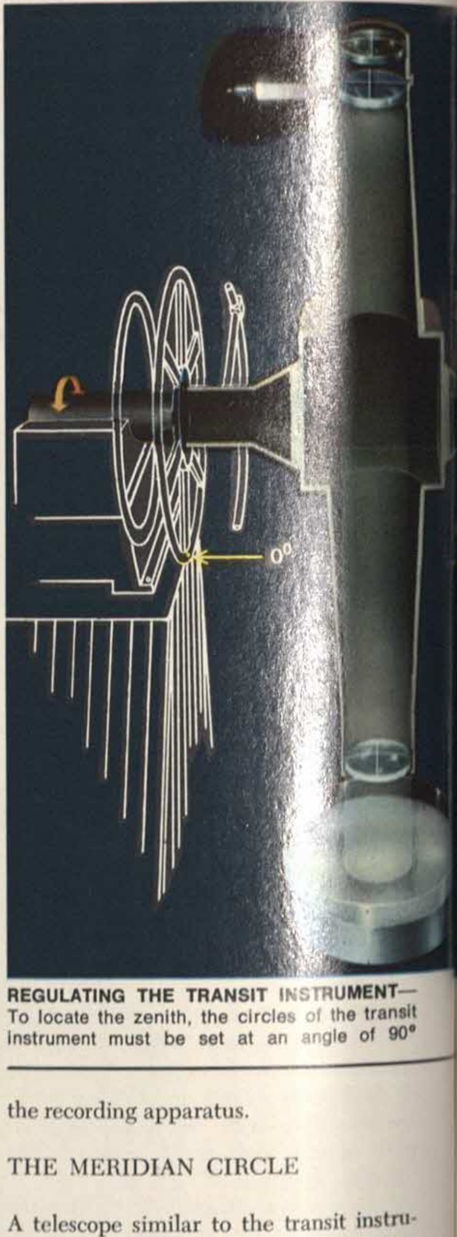
USES OF THE TRANSIT INSTRUMENT

The instant of a star's transit is established to obtain its celestial coordinates at the time of passage; if the star is a known star, the time of its transit on a given day will be known, and clocks can be set and regulated according to the findings of the transit. Finally, if the time and coordinates of a star are known, it is possible to fix with great precision the longitude on Earth of the point where the transit instrument is located. Thus the geographic coordinates of an observatory equipped with a transit are known with extreme accuracy, and a series of these observations serve as reference points to determine the dimensions of the Earth.

OBSERVING THE PASSAGE OF A STAR

The eyepiece of a transit instrument is equipped with a grid of two fine horizontal hairlines intersected by several vertical and parallel hairlines equally spaced. The transit is pointed so that the star, in its apparent motion, will cross the field of view of the instrument within the band bounded by the horizontal lines; the precise instants when the star crosses the vertical lines are to be obtained. (Before time was measured electrically, astronomers used the swing of a precise pendulum to measure the times when the star crossed each line of the lens.) Now the observer presses a button at the appropriate instant; this causes a mark to appear on a strip of paper on which a precision chronometer is simultaneously registering each fraction of a second. Later, when the paper has been removed from the machine, the correlation is observed between the marks. Even this method may be subject to human error—a slight delay in the pushing of the button, which in turn may be dependent on the relative brightness (and ease of perception) of the star. Therefore, many transit instruments are equipped with a photoelectric cell that reads the light of the star impinging on the telescope; at the instant the light is obscured by the interposition of the wire, an electric signal is registered by the recording apparatus.

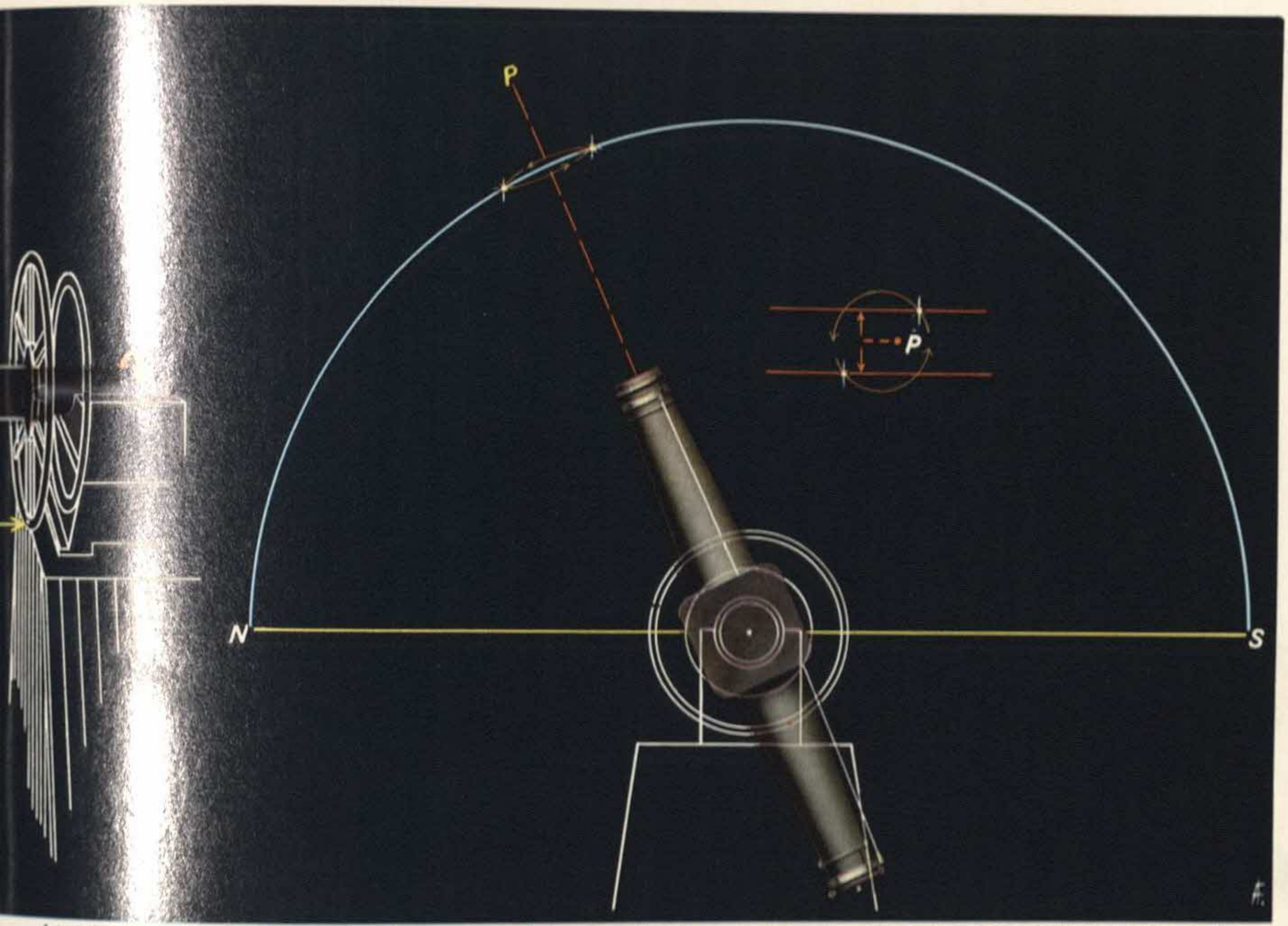
2



REGULATING THE TRANSIT INSTRUMENT— To locate the zenith, the circles of the transit instrument must be set at an angle of 90°

THE MERIDIAN CIRCLE

A telescope similar to the transit instrument, but with a slightly larger objective lens in order to obtain a clearer image of the star, is used when the altitude of the star at the instant of transit is of importance. In order to measure angles to the accuracy required, to one-tenth of a second of arc, the mounting of the telescope is equipped with a precise goni-



from the horizontal when the transit is in a precisely vertical position. This is done by sighting through the instrument to a pan of mercury below it, so that the cross hairs of the eyepiece coincide perfectly with their reflection in the mirror of mercury. The altitude of the pole is then calculated (drawing on the right) by averaging two fixes of any circumpolar star at an interval of 12 hours.

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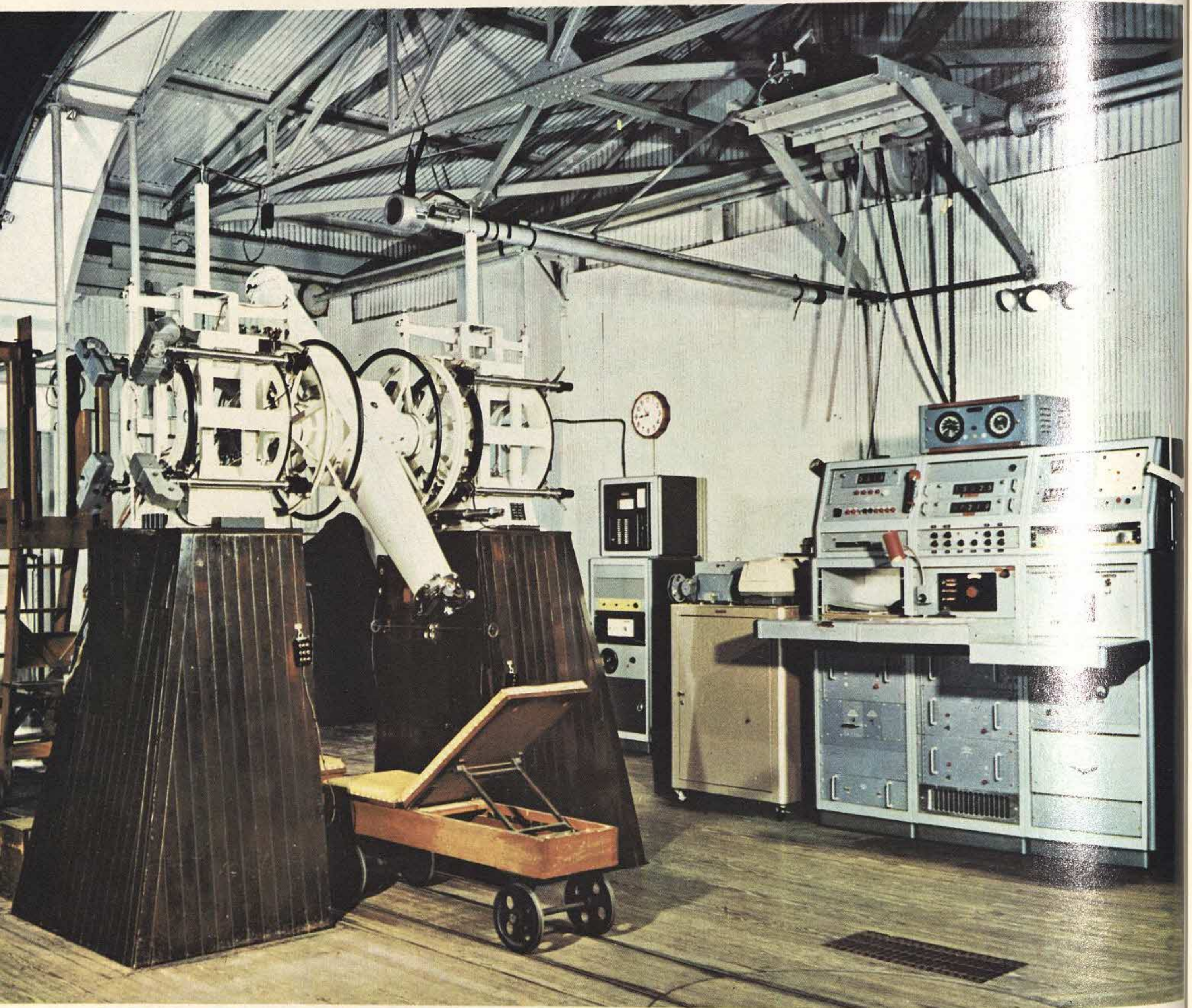
ometer, or circle. The calibrations on this circle are engraved in metal, and must have a tolerance not exceeding 0.25 μm (0.00025 mm). A microscope is necessary to take readings. A cross hair fixed horizontally in the eyepiece of the telescope is used as the track along which the star passes across the field of view; as the star crosses a vertical cross hair marking the meridian, the altitude as shown on the circle is registered. An important modification is use of the traveling-wire micrometer to avoid systematic error.

SETTING THE INSTRUMENT

In order to measure the altitude of a star, it is first necessary to make accurate measurements of two reference points: the zenith and the celestial pole. To find the zenith—the point directly above the observer—it is useful to locate its opposite, the nadir. This can be done by placing a pan of mercury below the instrument and pointing the instrument downward; when the image of the cross hairs, reflected by the horizontal mirror surface of the mercury, appears superimposed on the cross hairs of the eyepiece of the telescope itself, the instrument is in perfect vertical alignment. With the telescope in this position, the circle is set to read exactly 90° below the horizon.

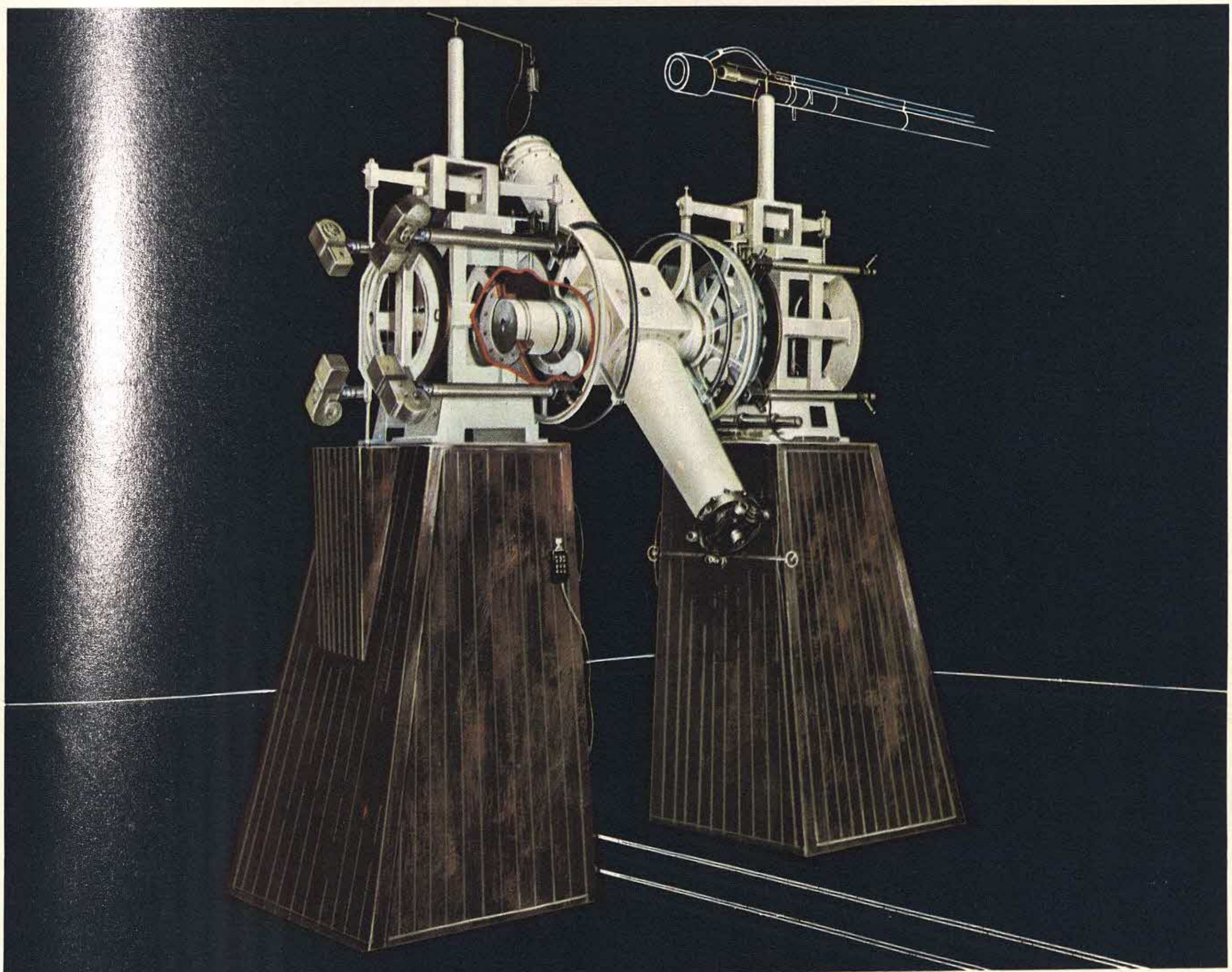
The celestial pole is located by taking two fixes, 12 hours apart, on one of the circumpolar stars (those stars between the Pole Star and the horizon, stars that never set). The average altitude of these two readings of the same star is



THE WASHINGTON MERIDIAN TELESCOPE— The computation of a star's altitude and the time of its transit make possible the compilation of very precise sky charts that are used to observe the motions of the individual stars, and are also used for celestial navigation. The U.S. Naval Observatory in Washington, D.C., founded originally to serve navigators, is now occupied primarily with scientific research. This photograph shows the sturdy supports, covered in wood, for the axis of rotation of the transit instrument; the supports rest on foundations independent of the building. A reclining chair rolls between the supports, and is used by the astronomer making observations. The panel of nine buttons on the left controls the automatic movements of the instrument. Along the right wall of the room are quartz chronometers and recording machines that automatically register on perforated tape the time of the transit of a star. The slit in the ceiling runs in a north-south direction, opening on the meridian.

the location of the celestial pole. With this altitude known, the celestial equator can be located, and from these all the other coordinates of the stars.

The transit circle cannot be turned to all parts of the sky; it moves in the meridian circle. Observations are made through a slit in the walls and roof. During a measurement with the transit circle, a faint artificial illumination shows the fine wires stretched across the field. Only one of these wires can be moved up or down by turning a micrometer screw; the rest are fixed cross wires. In the traveling-wire or "impersonal" micrometer, the observer continually turns a screw in order to keep a fine wire constantly bisecting the moving star image. The turning of the screw moves the eyepiece as well as the wire so that the bisected star remains apparently stationary at the center of the field of view. Electrical contacts are made when the moving frame reaches definite positions, and the time when the wire (and the star) reaches a series of positions is thus automatically recorded on the chronograph. The field is photographed several times, and the altitude observation is also recorded photographically. The whole observation takes two minutes or less, but then there is a great deal of computing to do. The form of the transit circle that came into general use was built in 1819 by the German astronomer Georg von Reichenbach.



DETAIL OF THE TRANSIT INSTRUMENT— This illustration shows part of the structure of the transit instrument in Illustration 2. The telescope revolves on an axis supported by two bearings, one of which is seen in the cutaway area bounded by the red line. After a series of sightings has been made, the telescope is reversed so that the pivot that previously rested on the west bearing rests on the east bearing and vice versa; thus, any error in orientation is reversed during the next series of sightings of the same stars, and the result is the correct measurement. To permit delicate rotation of the instrument, the horizontal axis is relieved of weight by a system of levers and counterweights. The angle of inclination is read on the circle, through four microscopes, to an accuracy of one-tenth of a second of arc.

THE CORONAGRAPH | artificial solar eclipse

A solar eclipse occurs whenever the moon comes between the Earth and the sun. Although the moon is far smaller than the sun, it is also far closer to the Earth than the sun; and, therefore, can completely or almost completely occult the sun. When the moon is closer than usual to the Earth and the sun is farther away than usual, the occultation is even more complete; but when the moon is more distant from the Earth and the sun is relatively closer, the rim of the sun appears around the occulting moon as a thin ring. The first type of eclipse is described as total; the second type is called annular, from the Latin word for "ring."

The sun, like all stars, has many layers; the layer normally visible, with an edge apparently well-defined to the naked eye (although a telescopic view reveals irregularities and flares), is called the photosphere. Surrounding the photosphere, however, is another layer of higher temperature, called the chromosphere. This layer is best detected by spectrographs, and is the actual source of solar flares and other prominences. Outside the chromosphere is an even hotter envelope of very rarefied gas that extends outward for millions of miles and is known as the corona. It has only a small fraction of the luminosity of the photosphere, which so outshines the corona that the latter cannot be seen except when a total eclipse entirely occults the photosphere. A total eclipse is the only natural phenomenon that reveals the corona; but scientists have devised an instrument—the coronagraph—that simulates a total eclipse and makes possible more convenient observations of the solar corona.

OBSERVING THE CORONA

When the brilliant light of the photosphere is entirely occulted during total eclipse, the radiations emitted by the corona become visible. This light has two millionths of the luminosity of the unocculted sun—about equivalent to the luminosity of the full moon. The most luminous part of the corona appears as a halo around the occulted disk, and fades out to the color of the background sky.

During a total eclipse, the shadow of the moon on the Earth is not black or even perfectly dark. The most deeply shaded portion, the umbra, receives light from the sky and from diffused rays of

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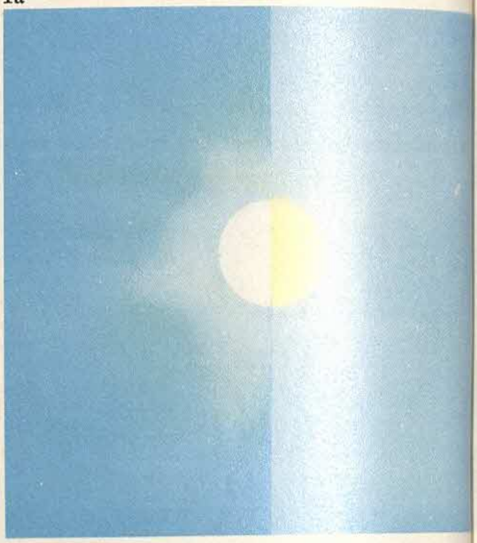
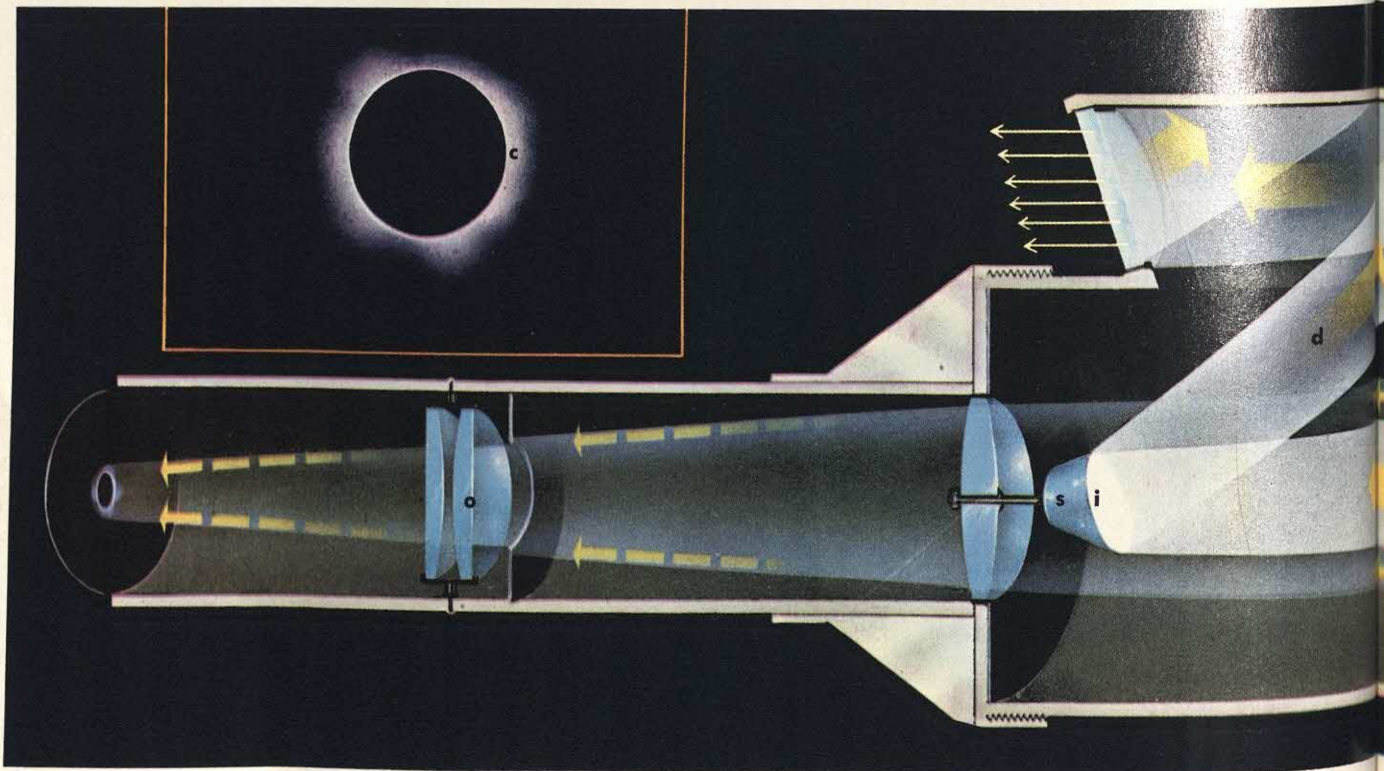


THE WORKING PRINCIPLE OF A CORONAGRAPH—At low altitudes, the light of the sun is diffused by dust suspended in the atmosphere, and the weak light of the corona remains invisible (Illustration 1a, right side); but if the air is free of dust particles, the corona is visible against the darker sky (Illustration 1a, left side). To observe the corona in the absence of a total solar eclipse, a coronagraph is necessary. In the telescope shown below, the image of the sun is occulted by a reflecting screen **s,** which deflects its brilliant light out of the tube **d.** Through the ocular lens **o** appears at the left only the image of the corona **c** (upper left).

1b



sunlight, and is brighter than if it were illuminated directly and solely by the full moon, or (what amounts to the same thing) by the solar corona.

THE CORONAGRAPH

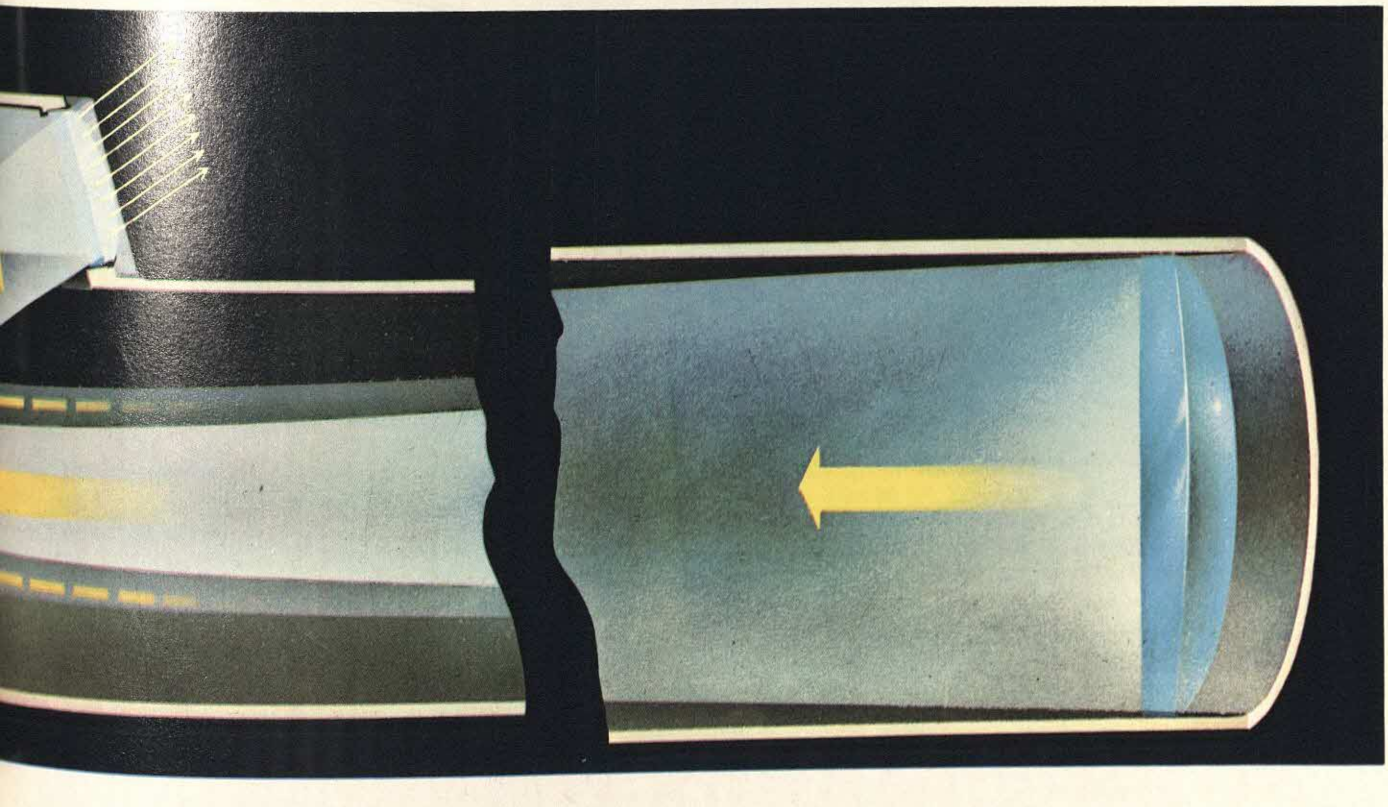
The special instrument devised for observation of a solar corona without an eclipse is the coronagraph. It was designed by a French astronomer, Bernard Lyot, who found that it was not enough to occult the sun with an opaque disk—for a corona does not appear if a disk is held in the hand to conceal the rim of the sun—but that it was necessary to prevent any light from the photosphere from outshining the corona.

The coronagraph is essentially a telescope. Its objective lens is trained on the sun, forming an image at the focus. Here an opaque metal disk is mounted, made slightly larger than would be necessary to occult the image, in case there might be a slight error in training the telescope. Theoretically, then, the sun's bright disk is covered, and it should be possible to see the corona, as if during an eclipse. However, even if the lens were carefully polished, it is possible that a scratch a few microns wide and perhaps two inches long might exist on the surface of the lens. If light fell on this scratch as it passed through the lens, its rays would be scattered and would outshine the image of the corona—within the tube of the telescope it would be twice as bright as the corona, and would render the coronagraph useless. What is more, the smallest irregularity in the polished surface of the glass, even if invisible, would have a similar effect. Particles of dust suspended in the air in the tube of the telescope could also diffuse an excess of light. To eliminate dust the tube is not only hermetically sealed, but its inside surface is smeared with grease to catch remaining dust particles.

Another possible source of light might be dispersion of rays from the solar image within the tube. It might seem that an opaque, blackened disk at the focus should be sufficient to occult the rays; but such a disk actually reflects at least one percent of the incident light, and this would amount to 50,000 times the light received from the corona. When this reflected light strikes the walls of the tube, even though these too are blackened, at least one percent of this light is in turn reflected back—and this amounts to 50 times as much light as that emitted by the corona. Therefore, to eliminate this light, the image of the sun is directed, not against a light-absorbent disk, but against a reflecting disk that diverts the rays from the objective lens at an angle to the axis of the telescope into another blackened tube; thereafter, the rays are deflected several more times, so that they are trapped before reaching the eyepiece.

Finally, in order to eliminate any light that may be diffused by microscopic flaws in the objective lens, an intermediate lens is placed behind the focus; here, the image of the occulted sun with its corona is again formed, and the second image is surrounded by diaphragms that block any direct light from the objective in the direction of the eyepiece. The light so blocked is reflected outside the main tube of the telescope, rather than being absorbed, so that the diaphragms are heated by the sun as little as possible; otherwise, the diaphragms would pass their heat to the air within the tube and distort the image.

All precautions for elimination of the diffusion of light within the telescope would be in vain if the atmosphere itself

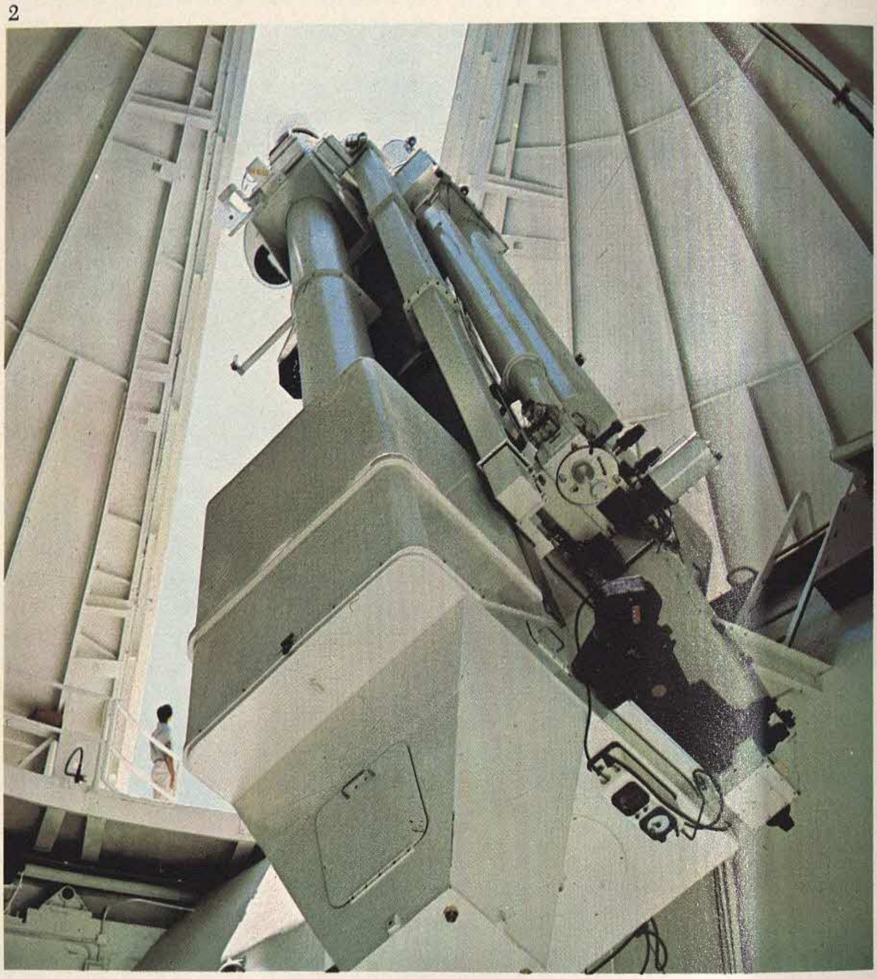


were not sufficiently clear. At an altitude of 150 or 180 m (about 500 or 600 ft) above sea level, a thick, overlying atmospheric layer—containing minute particles of dust, tiny crystals of sea salt, volcanic ash, meteorite powder, and droplets of water—prevents an unhindered view of the sun. Such a layer is something like the smog in the air over large cities, although more rarefied. Thin as it is, such an atmosphere would scatter the sun's rays and interfere with a view of the corona. The atmospheric dust remains constantly in suspension because it is constantly kept in motion and not allowed to settle, except at high altitudes of 2,400 m (about 8,000 ft) or more, where the dust can settle and the coronagraph can be advantageously used.

In 1931 Lyot successfully observed the solar corona in broad daylight, an achievement generally regarded at that time as impossible. He used his new form of telescope, much of which he carried on skis to the summit of the Pic du Midi in the Pyrenees (elevation 2,867 m (about 9,400 ft). By 1936 he succeeded in photographing the inner corona out to 7′ of arc from the sun's limb. With further instrumental refinements, and with the use of a polarizing monochromatic filter, Lyot by 1941 not only obtained pictures of the corona but also made direct photographs of the chromosphere, prominences, and sunspots that rivaled in quality those photographs obtained with the use of a spectroheliograph.

Two more coronagraphic observatories were built. The Zurich Observatory station at Arosa, Switzerland, has an elevation of 2,013 m (about 6,600 ft), and the Harvard station at Climax, Colorado, of 3,507 m (about 11,500 ft).

2



A CORONAGRAPH — This instrument works well only at high altitudes. The photograph (Illustration 2) shows a coronagraph at the Sacramento Peak Observatory in Arizona.

If the atmosphere is clear, the corona can be seen and photographed; it is also possible to see clearly the prominences that rise from the chromosphere and, with longer observation, their changing shapes. A monochromatic filter mounted in the focal plane aids in following these changes. To record the movements of the solar material and the corona itself, the sun may also be photographed with a motion picture camera.

ATMOSPHERIC DUST—At low altitudes the atmosphere contains minute particles that make it turgid. Above 2,400 m (about 8,000 ft) or so, however, this dust is not present, because the air is too rarefied to hold it in suspension. The curious effects are illustrated in this photograph (Illustration 3) of Broad Peak in Pakistan, which casts its shadow on the atmospheric dust below. The mountain in the right foreground is Gasherbrum.

3

THE MEASUREMENT OF ASTRONOMICAL TIME

clocking the stars

The duration of any event may be measured by noting the instant when the event begins and the instant it ends; the interval between these two times is the difference, arithmetically, between them. To make such a calculation, however, an instrument with appropriate calibration, such as a clock, is required. However, much more precise, and therefore more complex, instruments are needed to determine time intervals in technology and science.

Except for time, all physical measurements are based on units of which prototypes may be constructed and indefinitely preserved. A rod of a unit of length, such as that maintained by the International Bureau of Weights and Measures in France, is made of permanent material. A unit of time, however, can only be measured by a moving mechanism, such as a pendulum or a balance wheel, that can be regulated by external forces. Such a device must be free from any interference that cannot be predicted and verified. The only reliable standard for the measurement of time is the movement of a celestial object—in this case, the Earth. Any man-made clock—whether it is mechanical, based on the oscillation of quartz crystals, or even on the atomic oscillations of cesium—may stop someday, but the movement of the Earth will not stop except under circumstances that would make the measurement of time itself irrelevant.

One of the Earth's movements is its rotation around its axis, but this rotation is not at a constant speed because the tides, caused by the gravitational attraction of the sun and moon, slow it down periodically. Another of the Earth's movements is its annual revolution around the sun, but even this movement is affected by the movements of other planets. For this reason, a unit of time based on the Earth's movement—its revolution around the sun—was established with reference to a specific revolution: that beginning at noon on December 31, 1899. The solar (or tropical) year beginning precisely at that instant was divided into 31,556,925.9747 parts, and each of these parts was designated an ephemeris second. An ephemeris day is composed of 86,400 of these seconds.

The measurement of time in terms of the revolution of the Earth around the sun, or ephemeris time, is used for much astronomical calculation.

INSTRUMENTS FOR MEASURING TIME

Clocks are used to measure short time intervals—the time it takes an athlete to run a certain distance, the time it takes a missile to reach its target, the time taken by a proton to make a circuit of a particle accelerator. Two checks are usually made to determine the accuracy of a clock: its reading at noon of each day; and whether precisely 86,400 ephemeris seconds are recorded between two successive noons. Such checks are made by comparing one clock with another known to be relatively more dependable, or with the motion of the stars. Thus each clock must supply precise readings of instants of time and also keep pace with the motions of the stars.

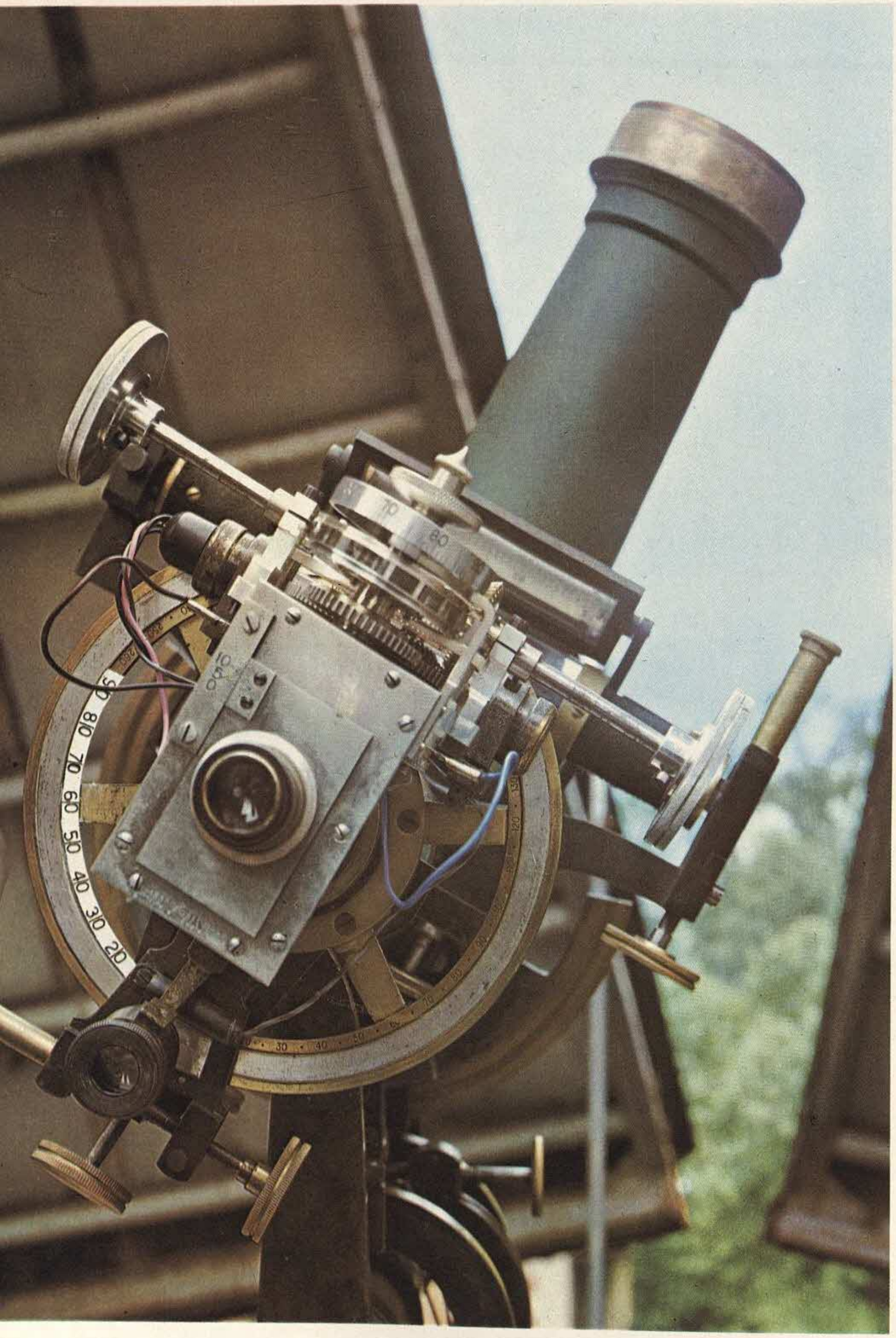
Measurement of the solar (or tropical) year—the time taken by the Earth to arrive at precisely the same position relative to the sun that it had previously reached (for example, the vernal equinox)—requires some way to determine when that position has been reached. This is done by sighting against the stars.

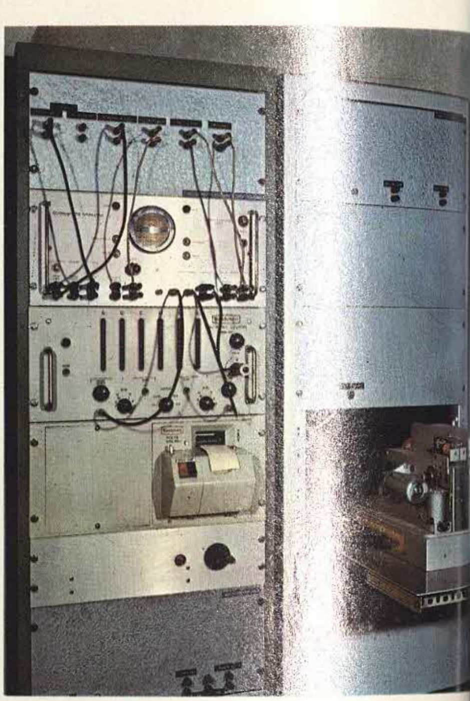
For periods of shorter duration, the rotation of the Earth around its axis can be followed by sighting the motion of stars over a fixed meridian. This is done by using a fixed telescope, called a transit instrument, trained along the celestial meridian. The eyepiece of this instrument is equipped with a hairline coinciding with the meridian. When this hairline bisects a specific star, the position of which is known, its time within a fraction of a second is noted; if this time coincides with the mathematically calculated time for that star to cross the meridian, the accuracy of the clock is confirmed.

The instruments for determining just when the star will cross the meridian are complex. The star is automatically sighted through the transit instrument; the instant the star crosses the hairline, a photometer mounted behind the eyepiece registers a diminution of the star's light, and an electrical impulse is emitted. This emission and an emission from the clock to be tested are sent to instruments called chronographs ("time writers"). These record indented lines on strips of paper, with an indentation on one strip for each impulse from the clock and an indentation on the other strip for the impulse registered by the star crossing the meridian. The task of the observer is to interpret the results by identifying the indentation for the star crossing in relation to the indentations of the clock. He can thus determine whether the clock was fast, slow, or precisely on time when the star crossed the meridian according to the transit instrument.

This check can be made on a piezoelectric quartz clock, which is operated not by a pendulum or a balance wheel (as are ordinary clocks), but by the oscillations of quartz crystals. Such a clock shows the time like an ordinary clock face, but also may emit electric signals every tenth, hundredth, or even thousandth of a second. However, such a long and complicated check cannot be carried out on many clocks, especially because at least ten checks are required to establish the required accuracy. This method is used to check one or two clocks at each observatory; these are considered master clocks, and other clocks are merely checked against them.

Accuracy exceeding even that of quartz crystal clocks can be attained by atomic clocks, which utilize small electrical and magnetic oscillations taking place in individual atoms. These vibrations are

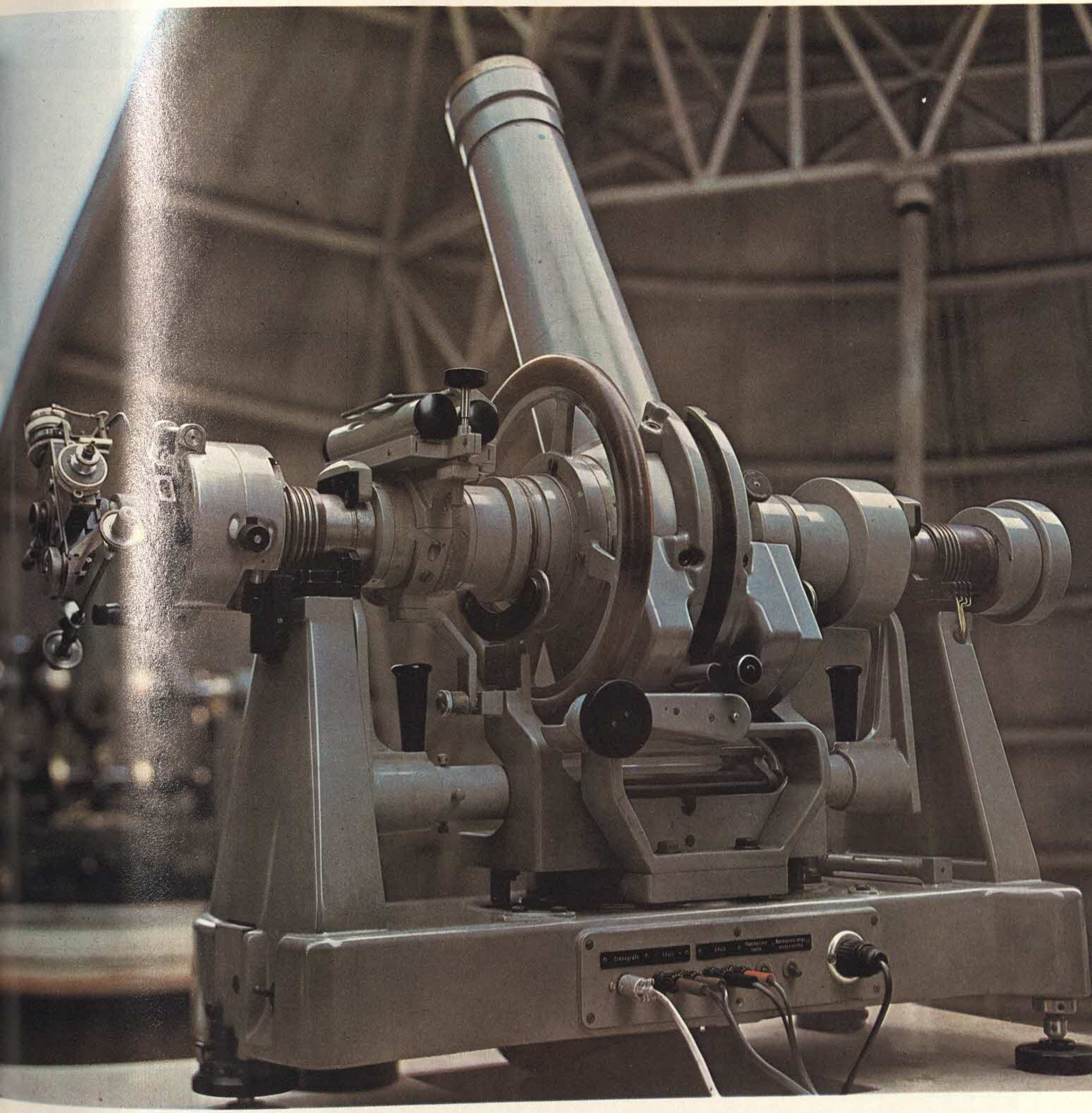




THE CHRONOGRAPH — This complex instrument (above) collects the electrical impulses emitted by the transit instrument and records them on a strip of paper.

THE TRANSIT INSTRUMENT—This telescope, also called a meridian circle, reads time by the motion of the stars. Just as an eye can observe the hands of a clock, the transit instrument, (right), supported on its massive mounting, observes very precisely the rotation of the sky past the meridian. It is the basic device for checking the accuracy of all clocks.

DETAILS OF A TRANSIT INSTRUMENT—This is a photograph of a transit instrument in profile. The known star, by which the rotation of the sky is measured, can be observed through the eyepiece at the center of the rectangular plate (left).



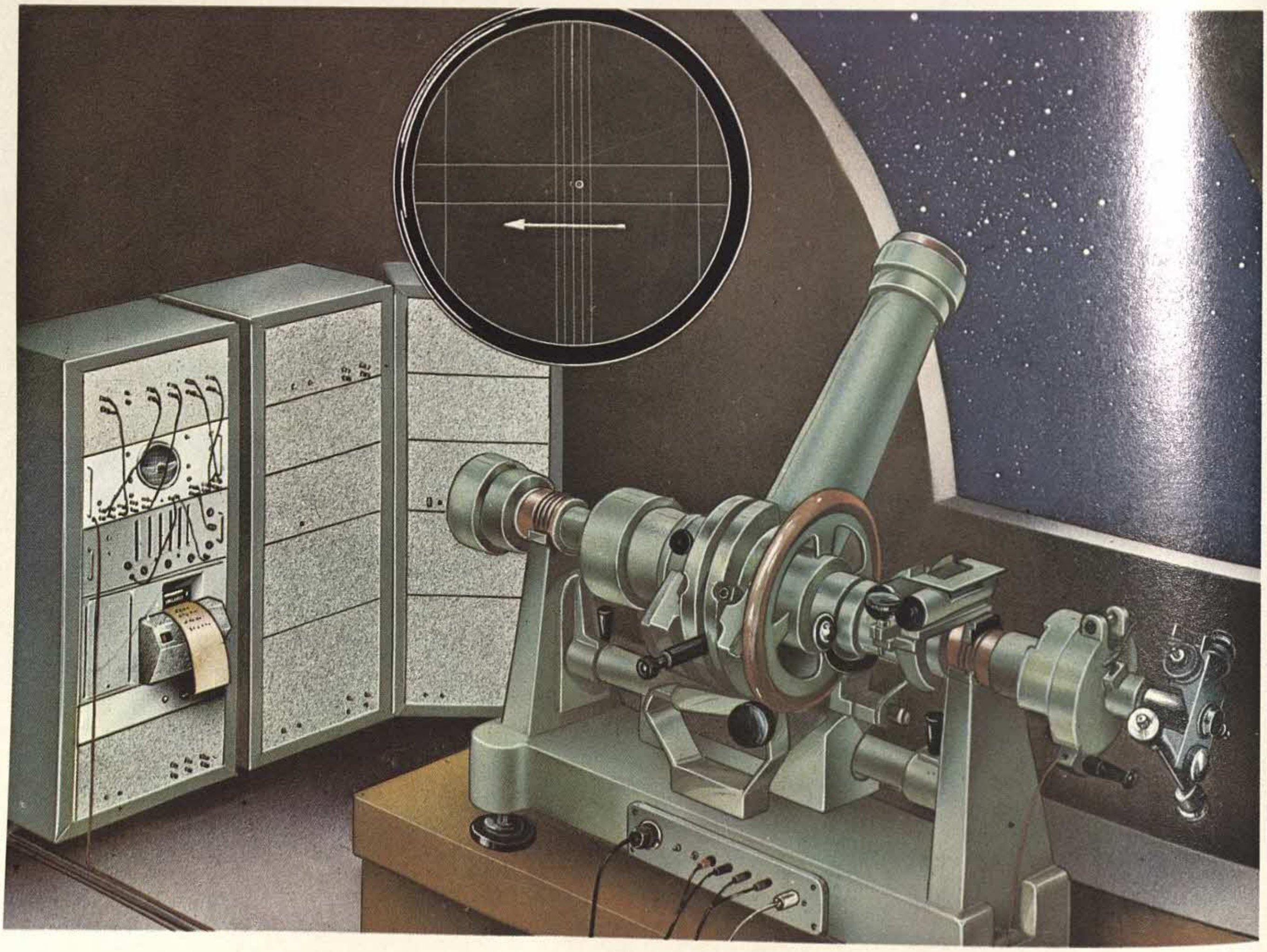
almost wholly independent of normal external conditions; and, as their frequencies are a property of the atoms themselves, they are identical for all atoms of the same kind. In one of the most commonly used types of atomic clocks, the atoms are those of cesium, the most electropositive element known.

Although writing chronographs were widely used in the second half of the twentieth century, efforts to reduce the time required for analyzing the results of measurements with writing chronographs led to the development of printing chronographs. These usually print figures from rotating type wheels, which are periodically synchronized with a controlling clock by means of electric timing signals. In a typical instrument of this kind, three wheels alongside each other carry type to print the minute, second, and hundredth of a second. One kind of printing chronograph that was used at the U.S. Naval Observatory printed a series of small marks instead of figures, and the time to the nearest five-thousandth of a second was read from the positions of these marks.

With the use of printing chronographs, however, there are erorrs resulting from the imperfect synchronization of type wheels with the controlling clock. Elimination of errors caused by the moving mechanical parts of chronographs has been made possible by the use of electron tubes and their associated equipment.

Complete automation in recording instants of time and in performing the necessary calculations has greatly simplified the measurement of time. The clock used in this test can be bypassed by a high-speed punch that records the time on tape for use in a computer or by a magnetic tape recorder. The tapes can be fed directly into computers, which automatically determine the exact time of passage of the star and also the time it should have passed, according to its known celestial coordinates. With such precise checking, the performance of any clock can be tested both as to its regularity and as to its correspondence with the motions of the stars and with the calendar.

THE OBSERVATION OF TIME—This illustration shows how astronomical instruments are set up for the measurement of time. The star is seen passing through the field of the eyepiece of the transit instrument. When it is briefly obscured by the hairline of the grid, the instrument emits electrical impulses; these are sent to the chronograph, which registers on paper strips the time of the star's crossing and the time given simultaneously by an accurate clock.



THE PLANETS THROUGH THE TELESCOPE | procedures for observation

The rules for locating the planets in the sky are fairly simple, especially when precise information about their positions at any given time is available in a celestial almanac. With a little viewing experience an observer can locate most of the planets without difficulty—whether a large telescope or simply a pair of binoculars is used. It is necessary only to know in advance what to look for and the best viewing method to adopt.

The planets are both the easiest and most difficult subjects for telescopic observation. Because they are easy to identify in the sky, it is easy to point the telescope at them; on the other hand, it is extremely difficult to observe small details with much clarity.

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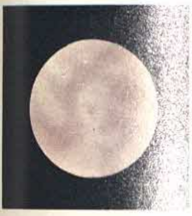

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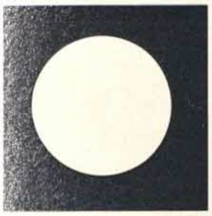

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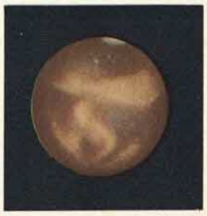

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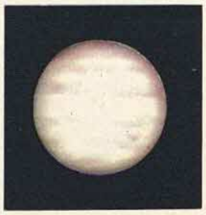

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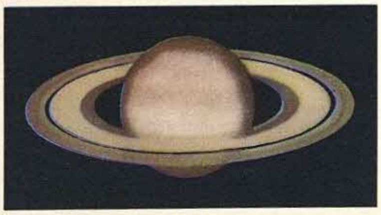

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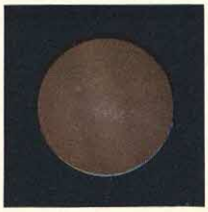

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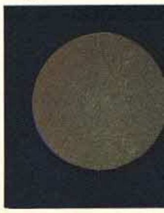

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THE BRIGHTNESS OF PLANETARY SURFACES—The effects of atmospheric turbulence and the small appearance of the images are two of the difficulties encountered in viewing the planets. A third difficulty stems from the difference in brightness of planetary images. Some planets are close to the sun and are strongly reflecting. Venus, for example, is like a bank of clouds illuminated by the sun. Other planets are less reflecting or more distant.

To observe the planetary images profitably, the eyes must adjust to their brightnesses. According to circumstances this can be done by various means, such as daytime and twilight observation, or special colored filters, or changing magnification, or stopping down the objective where magnification is low and where stopping down the objective does not lessen the clarity of the image.

In the illustration, seven of the planets are shown the same size but with different brightnesses due to the combined effects of the reflecting power of the planetary surface and the distance of the planet from the sun. The differences in brightness are considerable. The brightest planet is Venus (Illustration 1b); it is so bright that it is not convenient to observe it at night because the eye, being accustomed to the darkness of the sky, becomes insensitive to the details on the brilliant surface of the planet. If twilight observations cannot be carried out, it is best to wait for a full moon and then observe through a piece of dark glass, such as the lens of a pair of sunglasses placed between the eyepiece of the telescope and the eye, or between the eyepiece and the focus of the objective. Mercury (Illustration 1a) has a brightness only 40 percent that of Venus for a fixed combination of magnification and objective diameter; nevertheless, it, too, is so bright as to make night observation impossible. To see the details on Mercury's surface the planet must be observed during the day. This requirement, however, makes it particularly difficult to locate Mercury in the sky. Mars (Illustration 1c) has a brightness only 0.06 percent that of Venus, and it, therefore, appears even less dazzling in the telescope than Venus or Mercury. Nevertheless, Mars is still so bright that it is best to screen its image with a light filter of a greenish color (the same color as a thick neutral glass plate), which also serves to increase the contrast in the markings visible on the surface.

Jupiter (Illustration 1d) is 50 times less luminous than Venus; nevertheless, in the darkness of the night sky its light is still strong enough to prevent an observer from seeing details on the surface until the eyes have become accustomed to the light. The brightness of Jupiter, which is rather moderate, is adopted as a standard in measuring the brightness of the surfaces of more distant planets.

Saturn (Illustration 1e) has an acceptable telescopic brightness; it is one-fourth that of Jupiter. The brightness of Uranus (Illustration 1f) is 0.06 percent that of Jupiter, and Neptune's brightness (Illustration 1g) is about 0.002 percent that of Jupiter.

The brightness with which each planet appears in the telescope also depends—apart from the characteristics of the planet's surface and its distance from the sun—on the relationship between the magnification and the diameter of the objective. The lower the magnification and the larger the objective, the brighter the image. The data given in the illustrations apply only for a fixed combination of magnification and objective diameter.

THE RIGHT SKY

The observation of planets demands a good optical performance of the telescope and, above all, the right viewing conditions in the sky. To observe a planet it is necessary to obtain the optimum magnification from the instrument. Most telescopes have a set of several eyepieces, each of which gives a different magnification. The low magnifications give images that are bright and very clear, but small; the higher magnifications give images that are larger but darker, and, at times, less rich in detail.

To make satisfactory use of the higher magnifications, observation must be carried out under certain atmospheric conditions. To begin with, the stars must appear bright in the sky and not be dimmed or obscured by the presence of haze, smoke, or clouds. This is not, however, the most important requirement.

The essential ingredient for good observation of the planets is that the atmosphere be calm. In other words, there must be a minimum wind or turbulence, not only at ground level but also at high altitudes. Turbulence arises when air masses having different temperatures mix; these masses have different refractive indices that cause a flickering of telescopic images. The characteristic twinkling of the stars can be explained in the same way. Even though the twinkling of the stars may be a fascinating and poetic phenomenon, the conditions that cause it produce a considerable distortion of the telescopic images of the planets. It is best to wait for a night that is clear—but not one that is clear as a result of wind or a storm. In fact, a little fogginess is preferable to windy conditions.

The most suitable locations for telescopic observations are large plains surrounded by mountains, and large elevated plateaus, or tablelands. Attention must also be given to the fact that a location otherwise suitable in every way for observation could be completely spoiled by local or temporary conditions; for example, a slight breeze that brings the warm air of a distant chimney across the field of vision of the telescope is enough to ruin completely the quality of the image. For this reason, during the winter season observation through the apparently limpid, calm air of a city is often made practically impossible by the columns of warm air rising from countless chimneys.

APPARENT AND REAL DIMENSIONS, OPTICAL ILLUSIONS

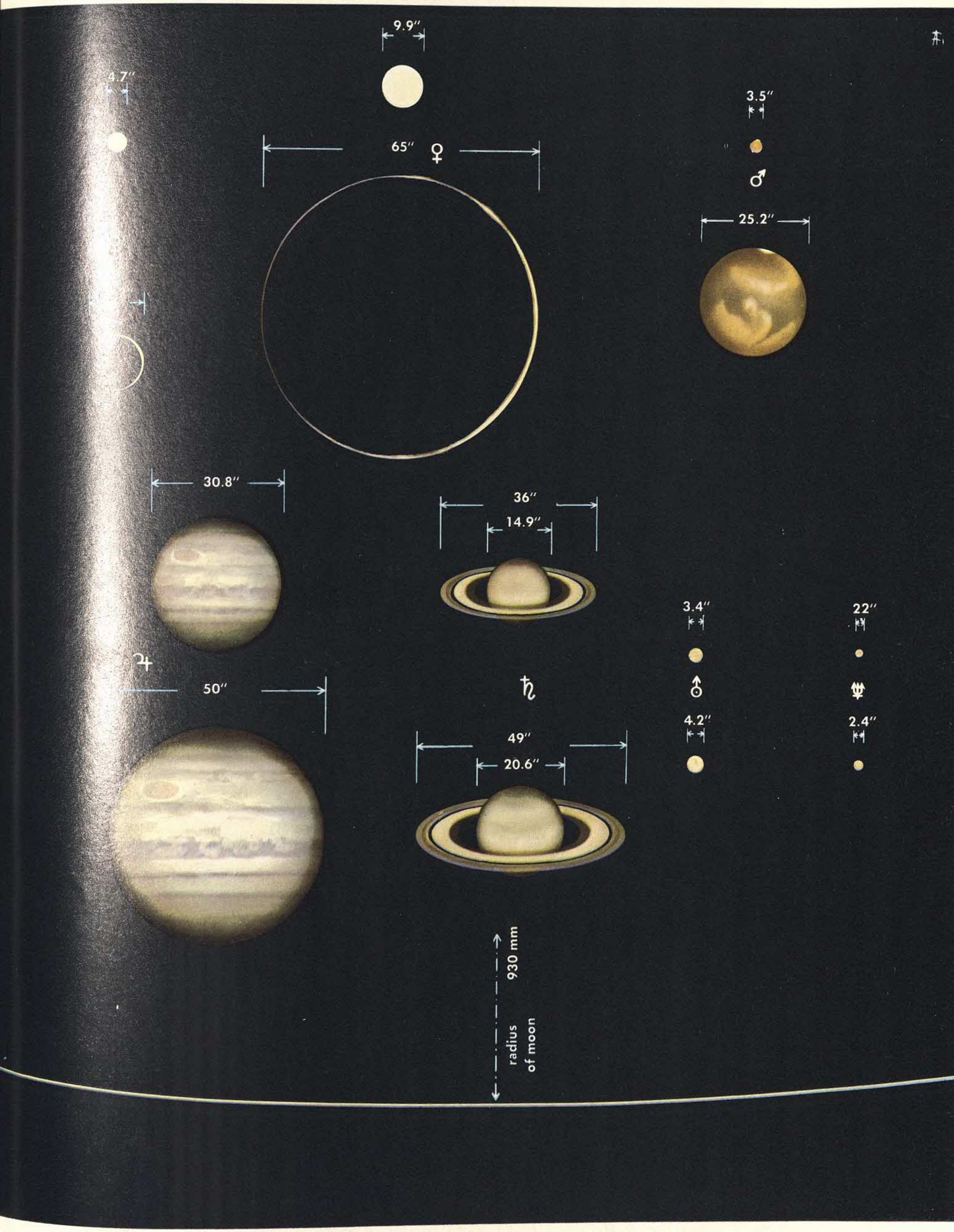
Observing a planet for the first time through the lenses of a large professional telescope is often disappointing because of the meagerness of the image. The first impression is of not being able to see anything on such a small disk—an impression that is heightened by an optical illusion to which everyone is subject. The images seen through the optical system of a telescope seem smaller than they really are. A simple experiment confirms this phenomenon. Tape a small piece of flat clean glass to one end of a box with at least two sides of approximately 20 cm (about 8 in.). Then, observe the image of a full moon as it is reflected in the piece of glass in such a way that in order to see it one must look downward or, at least, in a direction quite different from the one in which the moon is normally seen in the sky. The observer will then notice that the moon appears very much smaller than by direct observation, especially if the moon is close to the horizon.

Even when a planet is viewed through a telescope with a magnification that ought to make it appear as large as the full moon seen with the naked eye, it will, because of this optical illusion, appear much smaller. One must learn to distinguish details on the surfaces of the planets, even though the planetary disks may appear negligibly small. The dimensions of the planets as seen through a telescope are shown in Illustration 2; for comparison, a portion of the lunar disk is also shown. If viewed from different distances, these appear as they would in a telescope at different corresponding magnifications.

THE DIMENSIONS OF PLANETS IN THE TELESCOPE — The illustration shows how large the planets appear through the telescope. The images of planets have been drawn to a scale of 1 millimeter per second of arc. For example, the planet Jupiter appears with a diameter of 50 mm because at its minimum distance from the Earth its apparent diameter is 50″ (seconds of arc). (The apparent diameter of a planet is the angle generated by the line of sight when it is rotated between two diametrically opposed points on the planet's disk.) Each planet is illustrated twice to show the dimensions of its image at the minimum and maximum distances from the Earth. Some planets, such as those farthest from the Earth and the sun, have small dimensions even at minimum distances; Neptune is an example. Other planets, such as Mars, have highly variable dimensions depending on distance.

With a magnification of 200 an observer would see the planets in the telescope exactly as they appear in the illustration when viewed from a distance of 1 m (about 3 ft). At this distance all images are of appreciable size. This means that 200 X is quite sufficient to show the effective dimensions of all these bodies at whatever distance they may happen to be at the time of observation.

Viewing the chart from other distances, one can see how the planets will appear with other magnifications. With a pair of binoculars that magnify only 12 times, for example, the observer will see the planets as they appear in the illustration when viewed from a distance of 16.7 m (about 55 ft). At this distance the images would all be much too small to be measurable except for Venus, Jupiter, and Saturn, which would appear as very small disks or only slightly larger than luminous points. To see the planets as they would be observed with a magnification of 60 the chart must be viewed from a distance of 3.33 m (about 11 ft); at this magnification only Venus, Jupiter, and Saturn would appear as disks. Mars and Mercury, however, would have to be observed only when they are at their minimum distances in order to see their luminous disks and to discern some details on their surfaces. For a magnification of 120 the required viewing distance is 1.67 m (about 5.5 ft); for a magnification of 300, the distance is 67 cm (about 26 in.). With this magnification and an instrument having an excellent objective, a distinct image of most planets is visible. The line crossing the bottom of the chart represents part of the circumference of the moon.


9.9″
4.7″
65″ ♀
3.5″
♂
25.2″
30.8″
36″
14.9″
♃
50″
♄
49″
20.6″
3.4″
♅
4.2″
22″
♆
2.4″
930 mm
radius of moon

THE CONSTELLATIONS

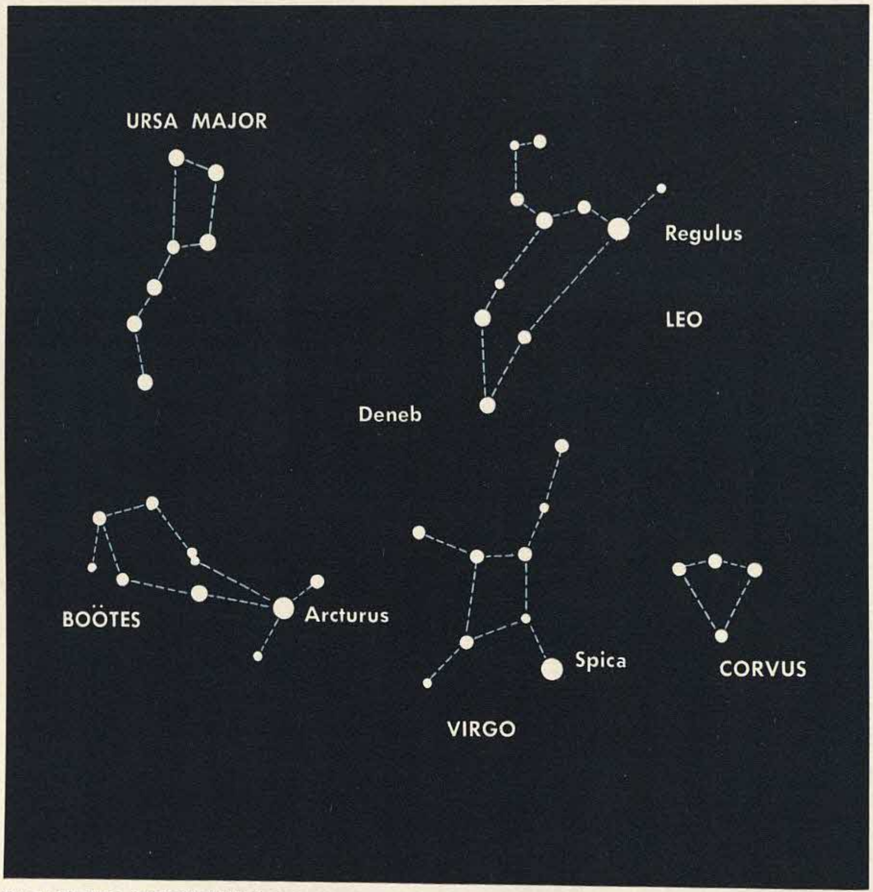
techniques of observation

In most cases the interesting celestial bodies that can be observed through the telescope are not easily visible to the naked eye. Experience and practice are needed to find them.

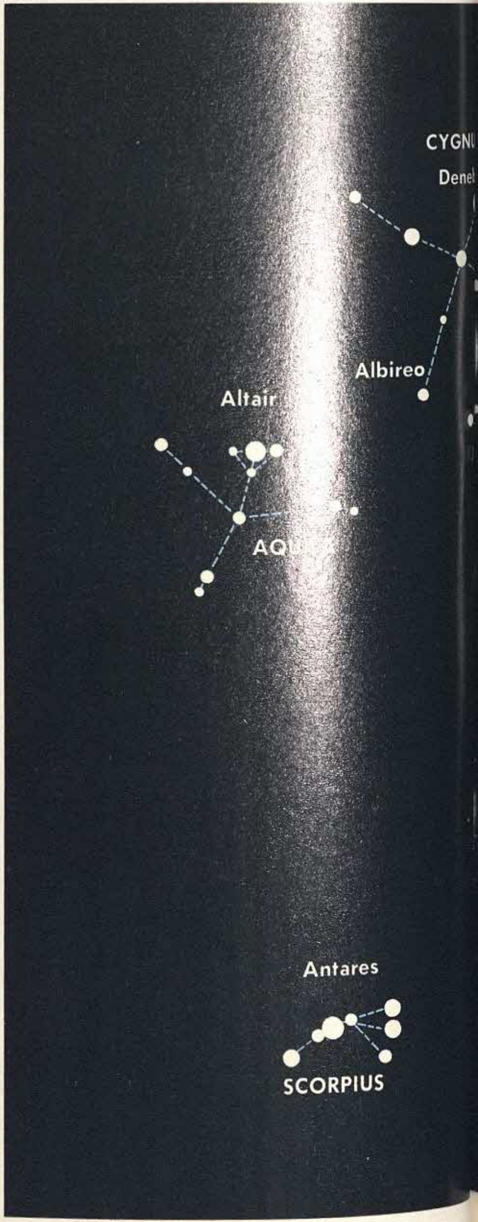
On a clear night the sky appears studded with stars of different brilliancies and located seemingly at random. An observer wishing to orient himself in this celestial labyrinth must first learn to recognize the principal constellations and their stars. Then, with the aid of star charts, he may proceed with both an in-depth exploration of the innumerable constellations, and identification of many of the celestial bodies that appear to intermingle with the stars.

HOW TO BEGIN

To study the constellations it is first necessary to memorize the design of a few of them. This can be done with the help of a few simple star charts, from which several examples are illustrated here. For those who are not familiar with constellations, use of the charts may be difficult at first, but with a clear sky and an unobscured horizon even the novice should soon be able to recognize at least a few stars. Once the first identification has been made it is relatively simple to find, with the aid of star charts, even the fainter stars. The stars shown here are the most luminous ones and are reliable guide posts in celestial reconnaissance.

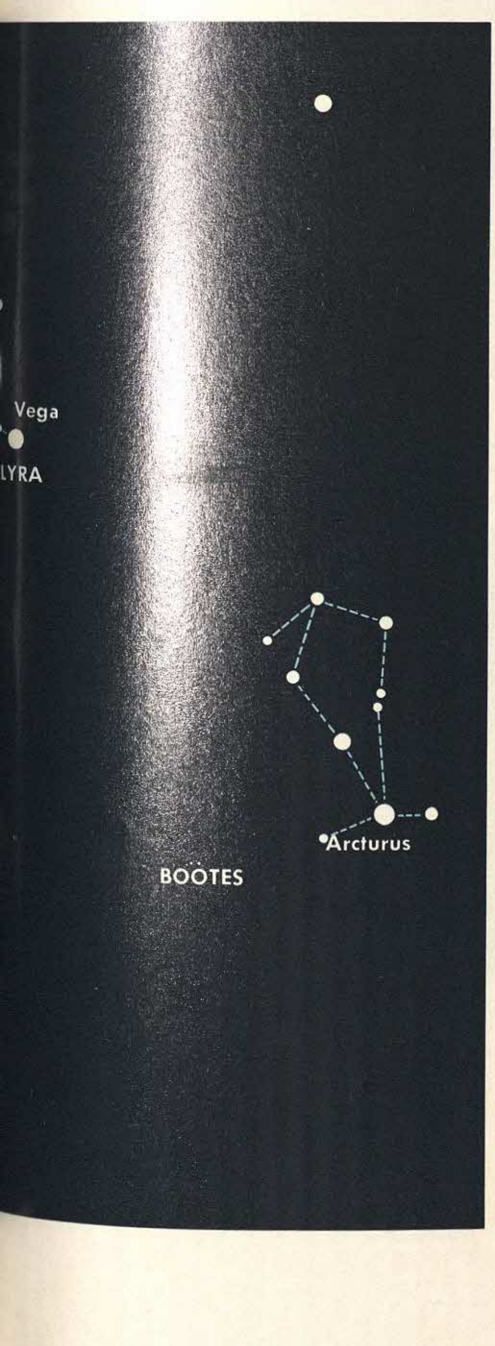


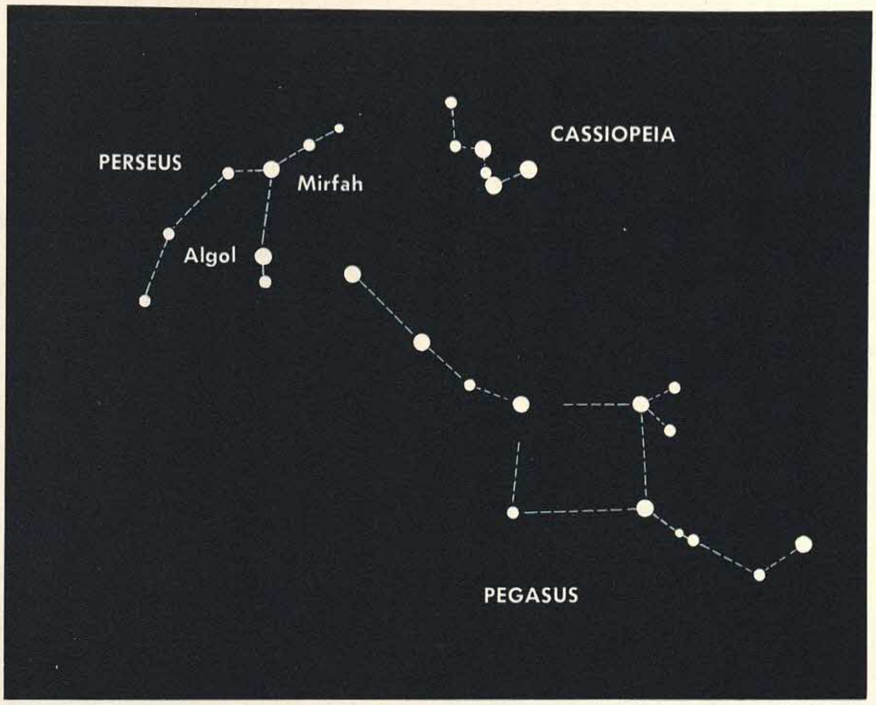
THE SPRING CONSTELLATIONS—A group of constellations is said to be pertinent to a particular season if it is visible high in the evening sky during that season. The northern constellations are always visible above the horizon, at any hour of the night and on any night of the year. However, these are exceptions to the rule. The other constellations appear only during certain periods; when they are visible, it is advisable to look for them while they are high above the horizon. They reach their maximum height and, therefore, visibility, in passing to the south, and it is in this position that they are seen in the evenings of their season of visibility. The illustration includes the constellations of Leo, Virgo, and Boötes. They are easily identifiable because of the characteristic patterns formed by their principal stars; an elongated trapezoid for Leo, a trapezium for Virgo. Arcturus, the most luminous star in Boötes, is aligned, as shown in the diagram above, with the stars forming the tail of Ursa Major. It is now possible to assign any star to its proper constellation.



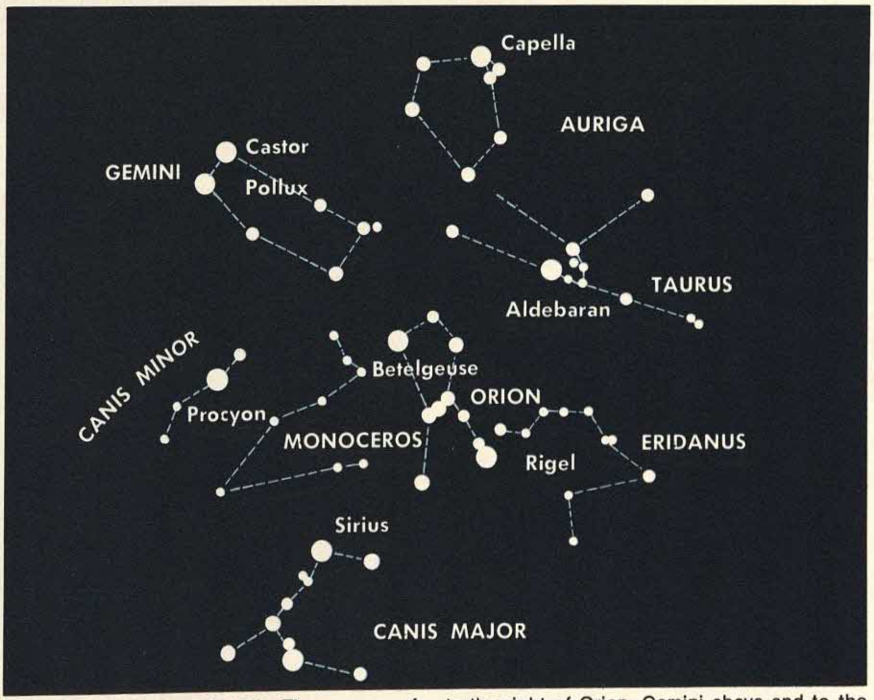
FOUR SUMMER CONSTELLATIONS—In the summer four important constellations are Cygnus (often referred to as the Northern Cross), Aquila, Scorpio, and Boötes. The fact that Boötes has already been observed as a spring constellation facilitates the identification of the group of summer constellations. The area covered by these constellations is so enormous that while the star Deneb, the most luminous star of the constellation Cygnus, is almost exactly at the zenith, the constellation Scorpio with its red star Antares is very low over the horizon where it is easily visible if the horizon is unobscured and the sky is clear.

No brilliant star is to be found at the center of the area covered by the four constellations, even though many celestial bodies are situated among the stars of the two weakly luminous constellations Ophiuchus and Hercules (not shown in the illustration below).





THE AUTUMN CONSTELLATIONS—In autumn no particularly luminous constellations stand out in the evening sky. There are few luminous stars, especially low over the horizon. Higher up is the beautiful group of stars that form the square of the constellation Pegasus. Beside it, to the left—toward the east—are the stars of the constellations Andromeda and Perseus. Very close to Perseus, but a little farther to the north, is the constellation Cassiopeia.



ORION AND ITS RETINUE—The group of winter constellations possesses a characteristic aspect that permits easy identification of individual stars. The constellation Orion, in the middle, is so prominent, because of its design and the luminosity of the stars composing it, that it can be easily located. Around this important constellation are other unmistakable ones: Taurus slightly above and to the right of Orion, Gemini above and to the left, Auriga directly above, Canis Minor to the left, and Canis Major below and slightly to the left of Orion. Sirius, the most luminous star of Canis Major, is so bright that it cannot possibly be misidentified. Also, it is aligned with the three stars (Orion's Belt) in the center of the constellation. Orion was named for the Greek mythological son of Hyrieus or Poseidon.

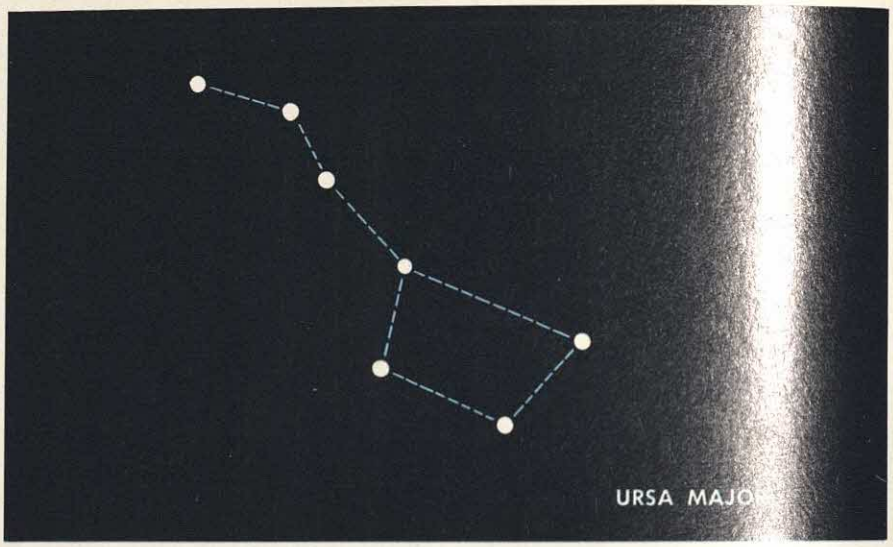
WHAT IS A CONSTELLATION—Ancient civilizations observed the sky more frequently than do people of today. In those times the stars were called on to serve as clocks, or calendars, and even to forecast the weather. The stars were, therefore, of fundamental importance to men and, for this reason, they were well known. In particular, it was noted even then that the stars appear to be grouped in certain distinct patterns; thus, each group of stars was given a name suggested by its pattern. The names were often those of animals or of mythological characters, and were assigned on the basis of pure imagination and fantasy.

Different civilizations have on occasion given different names to the same constellation. For example, the pattern of stars or constellation that is today often called Ursa Major (illustrated) was named the Dipper or the Pot by the ancient Chinese. It was called the Emperor's Chariot by a later Chinese civilization, the Hippopotamus by the ancient Egyptians, and the Wild Boar or Septembriones by the Romans.

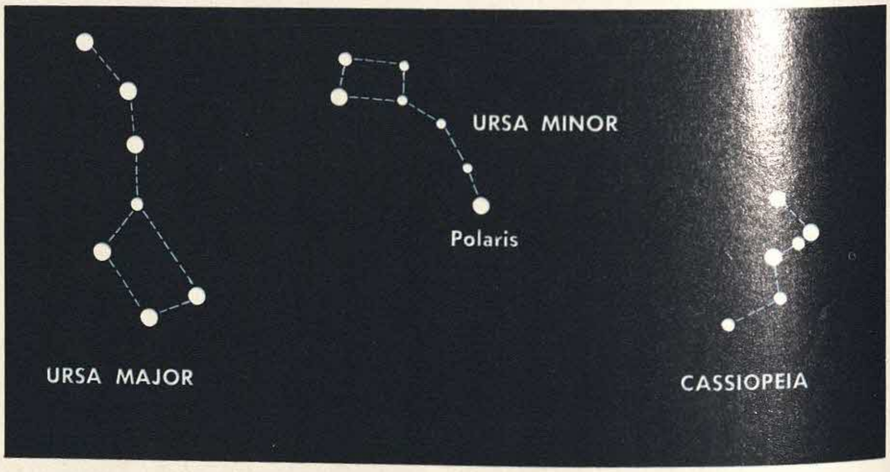
In modern times the concept of a constellation is used merely to indicate certain regions of the sky. If the sky is considered as a sphere and boundary lines are traced around each of the star groups, then one could say that those stars within the boundaries belong to the constellation. In the past zealous astronomers detached some small portions from the constellations, and then elevated these portions to the rank of new constellations, to which they gave any name that suited them. This state of affairs ceased when the International Astronomical Union codified the boundaries of constellations, placing them around the constellations not in an arbitrary way, but defining them with reference to arcs of celestial meridians or parallels.

The stars appearing to be grouped in a constellation are not necessarily particularly close to one another. In reality these stars are often at very different distances from the Earth; stars that appear as the most luminous of a constellation are sometimes the most distant, while the weaker ones may be closest to the Earth. To be able to state that a star belongs to a particular constellation, it is necessary that the direction in which it is seen falls within the boundaries of the constellation as determined by its principal stars. The principal stars that outline the constellation may be very much closer or farther away than the average of all the stars belonging to that constellation.

The star chart shows the principal stars of the constellation Ursa Major.



THE STARTING POINT FOR OBSERVATIONS—This star chart represents the northern portion of the celestial sphere with three principal constellations: Ursa Major, Cassiopeia, and Ursa Minor. The chart, like the following ones, shows only some of the most luminous stars of the three constellations and does not show other important constellations that are located between those represented. At this stage it is best to look only at the most obvious stars in a very simple pattern, in order to learn to identify the constellations themselves. In the charts that are shown later some of the more interesting details are included. The group of constellations illustrated is in the northern sky. The constellations will be seen in the position shown if they are observed, for example, on a spring evening at 9:00 P.M. Ursa Minor appears almost at the zenith directly above, while Cassiopeia is in the northeast. The North Star, or Polaris, is situated in the middle, so that Ursa Major and Cassiopeia are disposed symmetrically with respect to it.



STUDYING THE SUN | methods for observation

Although the sun is apparently the largest and brightest of the stars visible to the naked eye, it is actually among the smallest and faintest. The illusion of great size and brightness arises from the comparative nearness of the sun—the next nearest star is nearly 300,000 times as far away.

Since the sun's apparent light is billions of times greater than the light of the stars or planets, however, special equipment is necessary for solar observation, and special precautions must be taken to avoid permanent eye damage.

The sun may be observed through either a specially prepared telescope or a specially prepared pair of binoculars. Further study through a spectroscope reveals some of the atomic phenomena that take place in the solar atmosphere.

1

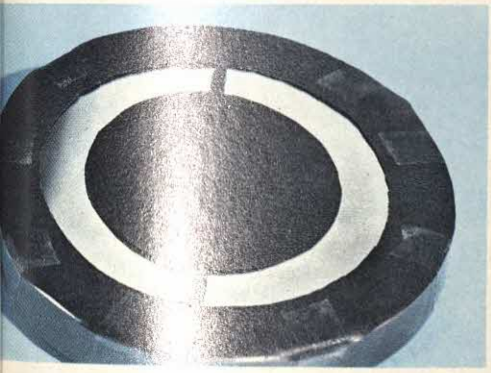
OBSERVING THE SUN WITH A TELESCOPE—The skywatcher who wishes to study the sun must use extreme caution, and must never look directly at it through the eyepiece of a telescope, even if the sky is heavily overcast by clouds and the sun appears dull. A gradual clearing of the sky might pass unnoticed by the engrossed viewer, and sometimes the sun suddenly shines through a break in the clouds. In addition, invisible infrared radiation—damaging to the eye—penetrates clouds and haze more efficiently than radiation of the visible frequencies.

If a conventional reflecting telescope is pointed at the sun, the concentrated image of the sun falling on the prism supports and internal walls of the tube will set the instrument on fire. In a telescope that is safe for solar observation, the amount of light collected by the mirror is reduced by covering the mirror with a commercially available sun filter or with a cardboard disk, such as that shown in Illustration 1a. This disk must be rigidly attached to the mirror so that it will not slip from place.

The amount of light delivered to the eyepiece must also be reduced. This can be done by covering the eyepiece with a portion of black and white (not color) photographic film that has been fully exposed to light and fully developed (Illustration 1b).

An even safer method is to obtain a sun diagonal—a device that employs a flat wedge of glass that permits direct observation of the sun with relative safety. The wedge of glass, known as a Herschel wedge, is a flat prism with an angle of about 10°. Such a prism, arranged much like a star diagonal, reflects about 5 percent of the sun's light, while the rest passes harmlessly through the glass wedge.

The safest way to study the sun, however, is by indirect projection—a relatively simple method. Some telescopes are equipped with a sun projection screen. The telescope is pointed at the sun by sighting along the tube through a double thickness of overexposed and developed photographic film. A piece of white cardboard is then held several inches from the eyepiece, and the telescope is adjusted until the image of the sun's disk is thrown onto the card. The image may be focused by racking the eyepiece in or out, or by moving the card closer to or farther from the eyepiece. This method demonstrates the solar phenomena as well as any other and is particularly well adapted for demonstrating sunspots.



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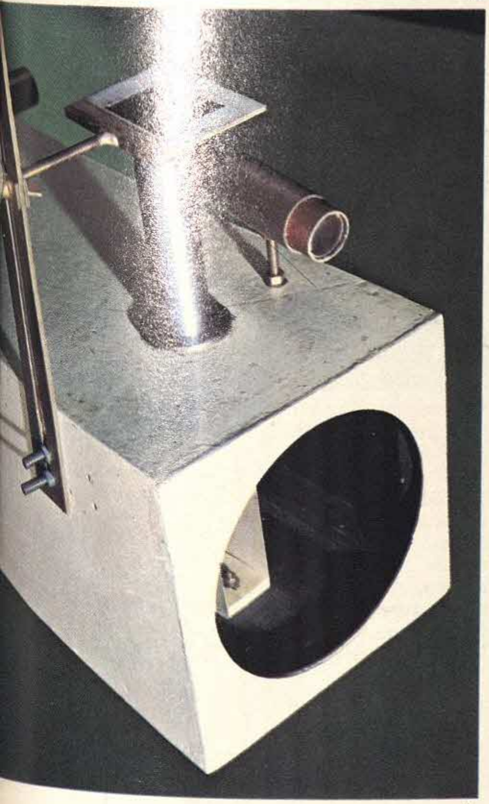
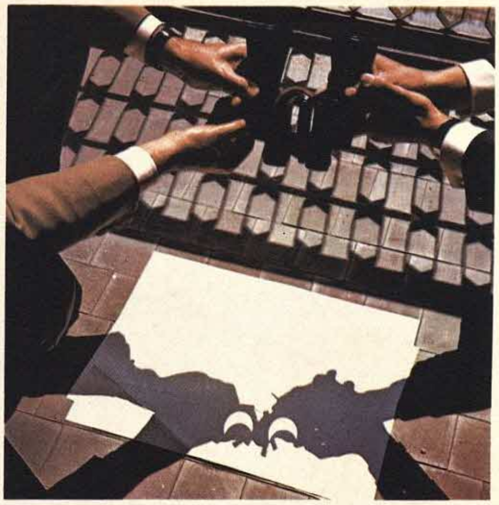


b

2

OBSERVING THE SUN WITH BINOCULARS OR A SMALL TELESCOPE—The binoculars or telescope should be pointed at the sun and focused until a sharp image of the sun is seen on a screen placed ½ to 1 m (about 1½ to 3 ft) from the eyepiece. A tripod may be used, or the arrangement shown in Illustration 2a. Because this experiment was carried out during a partial eclipse of the sun, the image appears as a crescent, rather than a disk. A photograph of the eclipse is shown in Illustration 2b.

a



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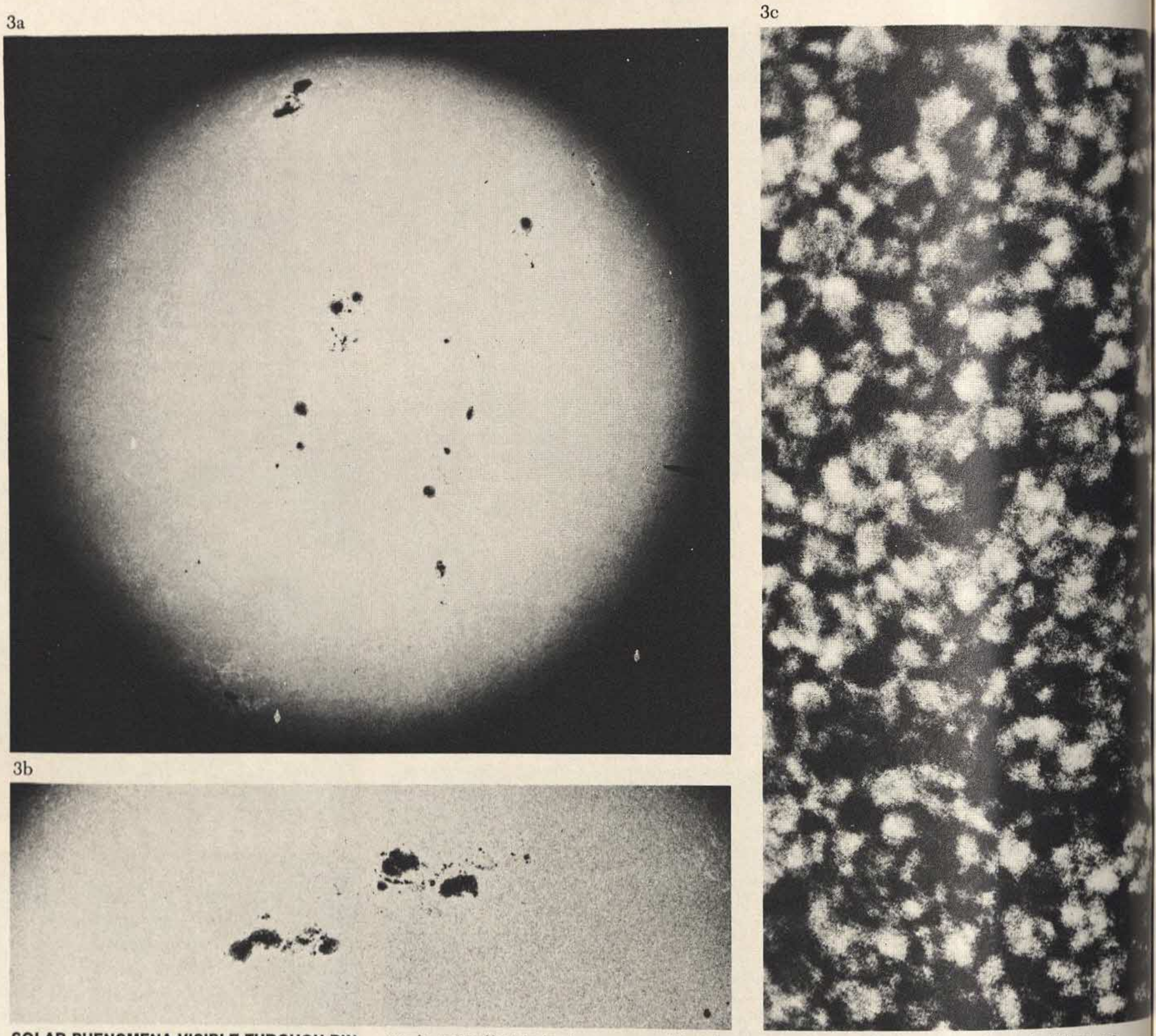


SOLAR PHENOMENA VISIBLE THROUGH BINOCULARS OR A TELESCOPE—These photographs show the five most commonly observed phenomena on the surface of the sun.

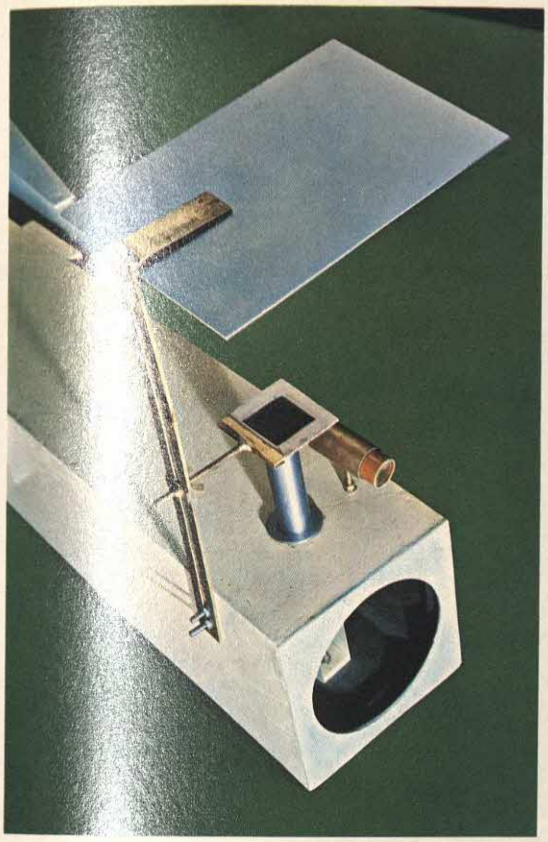
With a magnification of 40 to 80, a panoramic view of the sunspots and their distribution on the face of the sun is obtainable (Illustration 3a). Large bright areas, or faculae ("little torches"), are visible near the edge of the disk; these are associated with the sunspots. A third phenomenon is the darkening of the solar limb—the edge of the sun as seen from the Earth. This darkening indicates that the sun is not uniformly luminous, a condition due to the fact that the light coming from the sun's borders must cross a great thickness of partially absorbent solar atmosphere.

With a magnification of 120 to 200, the structure of the sunspots is visible (Illustration 3b). A sunspot has two distinct parts—a central darker region, the umbra, and a lighter surrounding region, the penumbra.

In very good atmospheric conditions, with magnification well over 200, the "rice grains" on the surface of the sun are visible. These are spots hotter than the surface of the sun, and are caused by hotter gases bubbling up from below the surface; they change shape every few minutes.

For best results, solar observations should be made when the sun is high in the sky. It is not possible to register a perfect image of the sun from the Earth, because the sun's heat causes atmospheric turbulence, which blurs the image. The best pictures of the sun have been taken from stratospheric balloons, or from space.

4



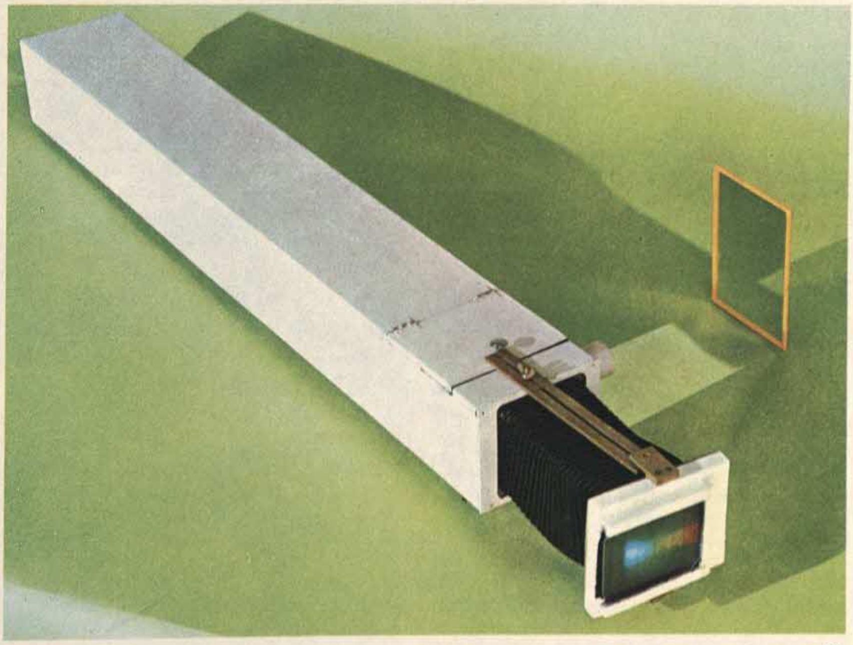
OBSERVING SOLAR ROTATION — Sunspots provide a reference point for observing solar rotation. A telescope with 40 to 80 magnification is focused on the sun until the image is as clear as possible. This image is projected onto a piece of paper attached to a screen, placed as in the illustration. The position of the sunspots is marked each day. After a few days, the sun's west-east rotation will be clearly seen by the change in position of the marked sunspots.

The sun is not a solid mass, and its period of rotation increases as the distance from the equator increases. At the equator, the rotation period is 24.65 days; at 60° N or S latitude, rotation takes about 31 days.

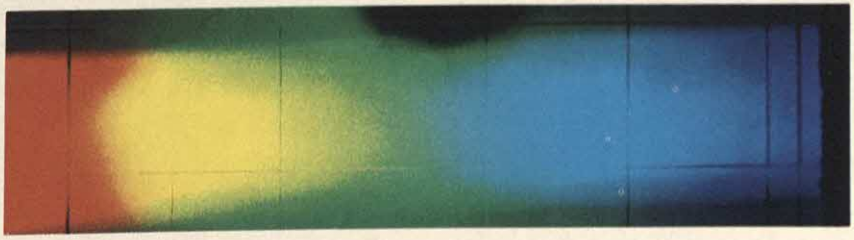
OBSERVATION OF THE SOLAR SPECTRUM— A spectroscope such as the one shown in Illustration 5a is placed so that it receives indirect illumination through a crack in a window opening to the south. A mirror is placed near the window sill so that it receives and reflects the sun's rays onto the slit of the spectroscope, parallel to the axis of the collimator.

Illustration 5b shows the image of the solar spectrum projected onto a ground glass screen.

5a



5b



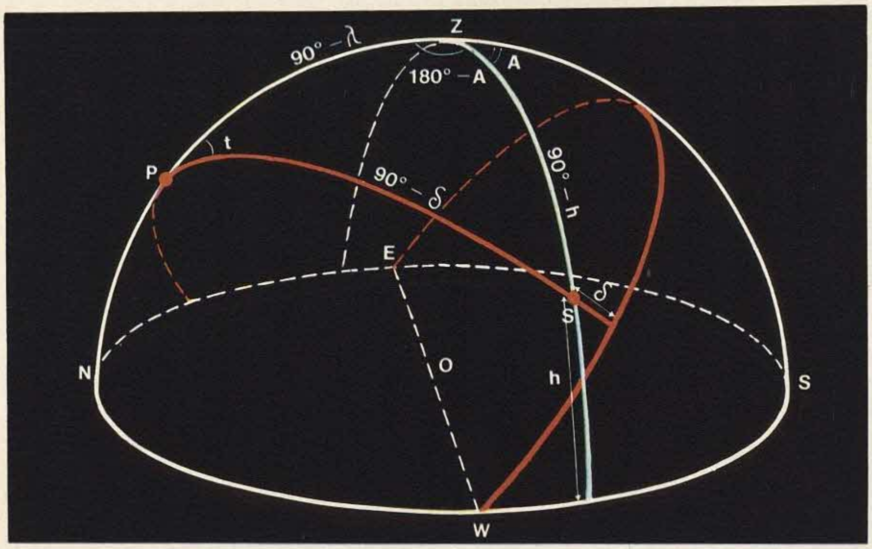
CELESTIAL NAVIGATION | astronomical determination of position

THE ASTRONOMICAL TRIANGLE—The basis of astronomical determination of the Earth's position is the astronomical triangle, as represented in this diagram. This is the triangle formed on the celestial sphere by three points: pole, zenith, and star, indicated here by the vertices **P, Z, S.** According to spherical trigonometry, a triangle is perfectly determined when three of its elements have been determined. The figure δ indicates the declination of a given star of known position; therefore, $90^\circ - \delta$ is one of the sides of the astronomical triangle that may be considered as correctly identified. The line **h**—the height of the star above the horizon—is measured with a sextant; thus, the side of the triangle that lies between the zenith and the star ($90^\circ - h$) is also known.

Assuming that the longitude of the position of observation is known, the value of the angle **t** can be calculated by noting the longitude, the time of observation, and the star's right ascension. With these three elements of the triangle known, the fourth element can be calculated. This is the side indicated as $90^\circ - \lambda$ (λ is the latitude, supposedly unknown, of the place of observation).

If the value of the latitude is known, the value of the angle **t** and hence the longitude may be calculated by using the value of the angle **t**.

1

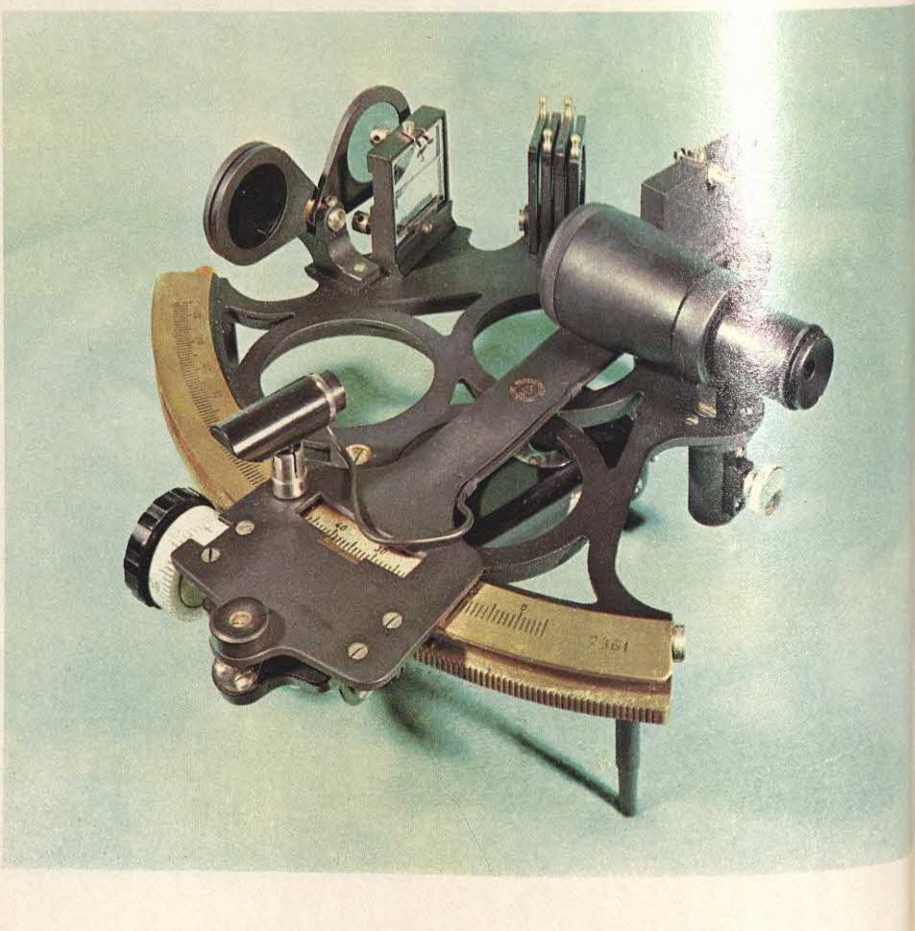


2

THE SEXTANT—The sextant is a portable telescopic protractor used to determine the elevation of a star above the horizon. Its working principle is simple. The horizon is observed through a semitransparent mirror placed before the telescope. The same mirror brings to the eyepiece the image of a star reflected in a second mirror placed above and controlled by a movable arm or alidade, which terminates at the edge of the goniometer or protractor. By manipulating the alidade, it is possible to superimpose the image of the star on that of the linear horizon. In front of both mirrors are several filters used for observing very bright objects such as the sun and the moon. In the case of the sun, it is not only too bright for direct observation, but the horizon below it is often too luminous for its limits to be clearly perceived by the eye.

For use when flying at great heights, or during the night when the horizon is not visible, some sextants are fitted with a device that creates an artificial horizon. This device consists of a reflecting surface, such as mercury or a mirror suspended from a pendulum and kept horizontal by means of gravity.

Sextant angles are usually read to the precision of one minute of arc. By frequently repeating the same observation, an average reading is obtained, and accidental errors due to instability of the instrument or imperfect observation caused by vibration of a ship or plane are avoided.



Man long ago discovered how to pinpoint locations on Earth by observing relative locations of the celestial bodies. This knowledge was vital to the early exploration and resultant colonization of various parts of the world, and it is still important for many purposes. Determining the precise latitude and longitude of a land position is necessary for the making of accurate maps and topographical charts. At sea or in the air, determination of the position of a ship or plane is essential to navigation; a ship's captain or a pilot must know how far he has traveled, how far he still has to go, and whether the course being taken is the correct one.

The principles for determining latitude and longitude are the same on land or at sea, but the methods that are used differ. On land, coordinates are primarily concerned with map making, which requires a high degree of precision. Navigation, on the other hand, requires only a level of precision that avoids major errors in calculating a safe route of travel. Usually, the nautical mile (corresponding to one degree of a terrestrial meridian arc) is a precise enough measurement for the navigator.

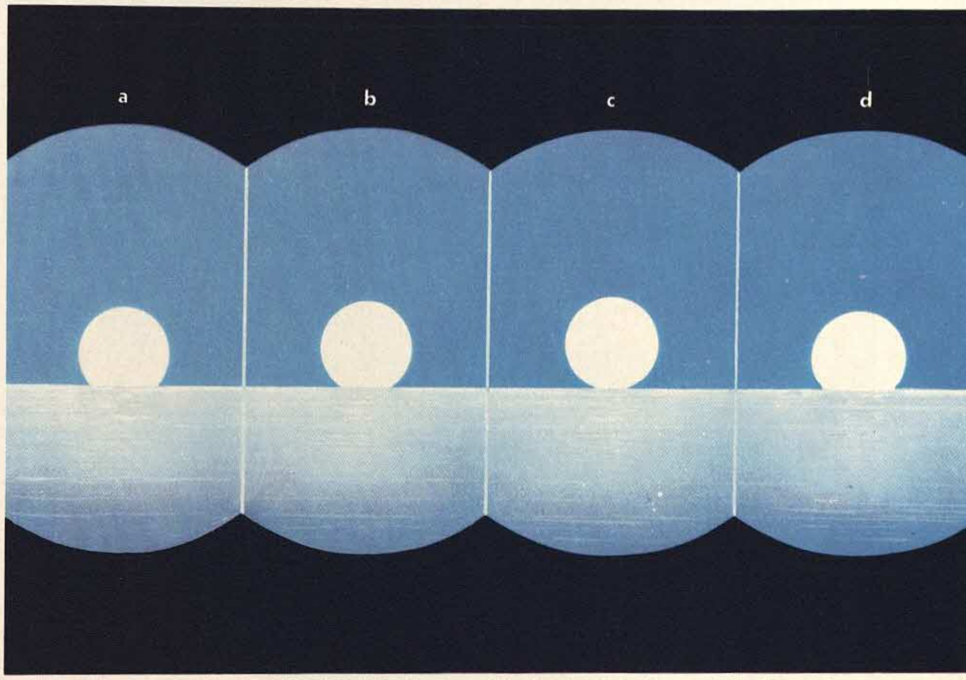
Another difference between methods is that on land, large, stable instruments can be set up on solid terrain to make measurements. In navigation, the movement of the ship or plane prohibits the use of any instrument except the sextant. Still another difference is that on land there is usually more time for the job, because it involves calculating the position of an unmoving object with respect to geographical coordinates. At sea or in the air, the position of the observation point is continuously changing—in the latter case, at high speed.

While radar systems have greatly eased modern maritime navigation, celestial observation is still important for ships on the high seas far from radio transmission stations. Celestial navigation must also be relied on when ships must maintain radio silence, as under wartime conditions.

Methods of celestial navigation (perhaps it would be more correct to say celestial guidance) are used in missiles and spacecraft. At great heights above the Earth, where the atmosphere is rarefied, stars are readily visible during the day as well as at night, allowing the use of telescopes to determine a reference point that constitutes a known angle with the rotation of the Earth on its axis. With this information, the course of the missile or spacecraft can be calculated.

Systems of celestial navigation are being gradually replaced by systems of inertial navigation, which are independent of terrestrial reference points and require an operator only to read the updated coordinates of the vehicle's position, and by artificial Earth satellite systems. Nevertheless, an understanding of the principles and methods of celestial navigation is of basic importance.

3



DETERMINING LATITUDE FROM THE SUN'S MERIDIAN ELEVATION—A theoretically sure way of determining latitude is to determine the elevation at which the solar disk passes above the meridian line with relation to the observation point. In practice, if the longitude is unknown, it is impossible to know the exact time when the sun passes the meridian line; sextant observations must be begun shortly before the approximate time of the sun's passage. During the first observations (Illustrations 3a and 3b), the alidade is continually moved in one direction. At the moment of the sun's meridian apex, it seems to rise no higher above the linear horizon (Illustration 3c). Instead of moving the alidade back toward its original position (Illustration 3d), the corresponding angle is read, directly measuring the sun's meridian elevation.

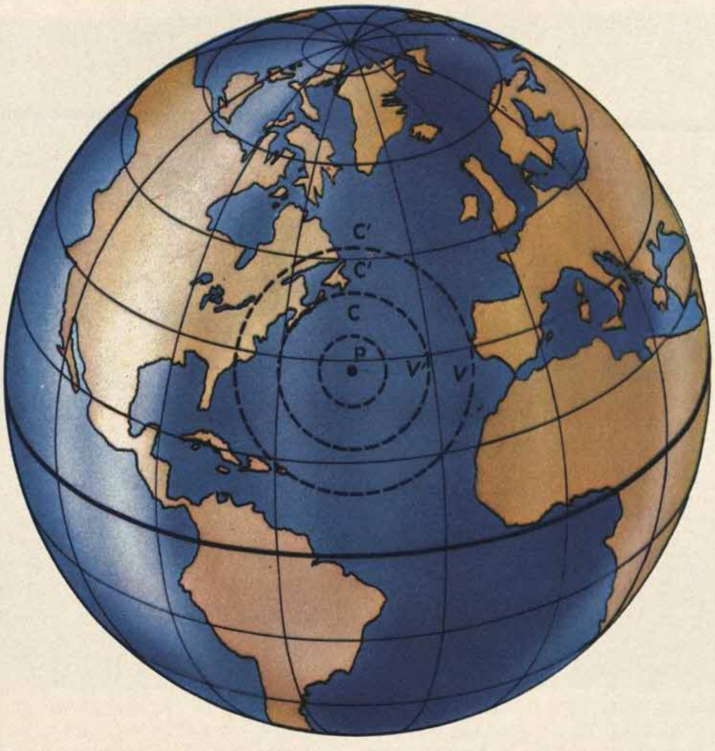
THE DETERMINATION OF COORDINATES

The geographical coordinates of a given observation point are found by means of observations and calculations. It is also possible to determine the coordinates of a star by using the meridian circle. The positions of the planets are calculated and published yearly. The positions of the sun and moon are similarly calculated and tabulated as aids to the navigator.

In practice, astronomical calculations can often be simplified. Nevertheless, the principle that serves as the basis for the determination of a given point—longitude and latitude—must first be understood.

Latitude may be determined if the declination of a given star—its angular distance from the celestial equator—is known. This celestial coordinate determines the height at which the star passes the meridian, and depends on the latitude of the point of observation. For example, if a star with a 30° north declination passes the meridian at 70° above the horizon, the point of observation is 40° north. The determination may be made even if the star does not appear on the

4



THE SINGLE OBSERVATION POINT—At any one time, a given star can be observed reaching its zenith (this point is indicated as **p**) from only one point on the Earth's surface. At the same time, at all points on each of the concentric circles surrounding **p** (**C, C', C''**), the star appears at the same distance from the zenith—that is, at the same elevation. These circles are called position circles. If a ship's navigator considers that, based on the speed and direction of his vessel since the last reading, it has arrived at **V**, the determination of the star's elevation indicates that it is located in circle **C'**. The actual location **V'** is at the intersection of circle **C'** and radius **PV**.

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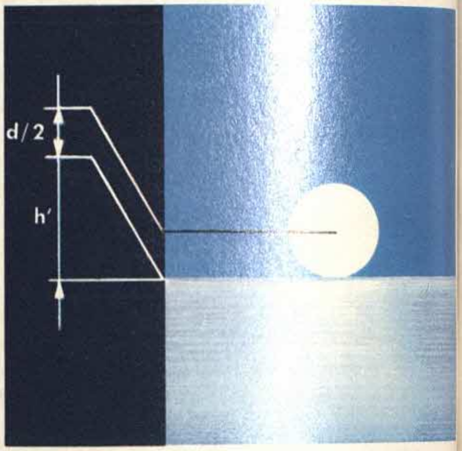

SEMIDIAMETRICAL CORRECTIONS—When taking a latitude reading as described in Illustration 3, it is necessary to measure the meridian elevation of the center of the solar disk. However, the sextant only allows measurement of the meridian elevation h' of the sun's lower edge. To obtain the required data, the value of the measured angle must be added to the angular diameter of the sun's radius (called the semidiameter, and indicated in the illustration as **d/2**).

meridian, by means of simple calculations that reduce the observation to that of the meridian. However, to make the calculation, the longitude of the point of observation must be known.

To determine longitude, it is only necessary to know the time that the star of a determined right ascension passes the meridian; for, if a star passes the meridian at a given time and place on Earth, it will pass at a different longitude either earlier or later in proportion to the longitudinal difference (earlier if east, later if west). In navigation this measurement is not easy to make, but the result can be obtained by determining the star's position—however distant from the meridian—and successively reducing the observation to the meridian. In this case, the exact latitude of the reference star must be known.

Thus it is not possible to make a determination of position with only one latitudinal or one longitudinal observation; one must be known in order to find the other, a seemingly insoluble problem. However, by knowing the coordinates of the point of departure and proceeding by approximations, a navigator can obtain a reasonable knowledge of position, allowing for some margin of error in measurement.

In the past, the location of a point was established by measuring a star's position once for latitude and once for longitude. Between the measurements, the route being traveled was estimated, along with the presumed change of latitude (for the calculation of longitude) or of longitude (for the calculation of latitude). The measurements were then progressively corrected. Modern methods, such as electronic radio-location systems developed during and after World War II, have simplified the process of navigating.

STARS AND CHRONOMETERS

Which stars are used to determine position? One guiding principle is that the greater a star's luminosity, the easier it is to observe. Therefore, by day, the sun is the most useful star for determining position. At night, the moon is the most useful celestial object—when it is visible. Next are the planets, particularly those that move slowly (such as Jupiter and Saturn) and require only simple calculations to determine their positions in the sky. On nights when the planets are not visible, the most luminous stars are used. On a clear night, any star may be so used, provided it is bright enough to be easily sighted through the eyepiece of a sextant. In cloudy weather, the brightest star must be used so that it can be identified with certainty and can be readily perceived through haze and overcast skies. Both stars and plan-

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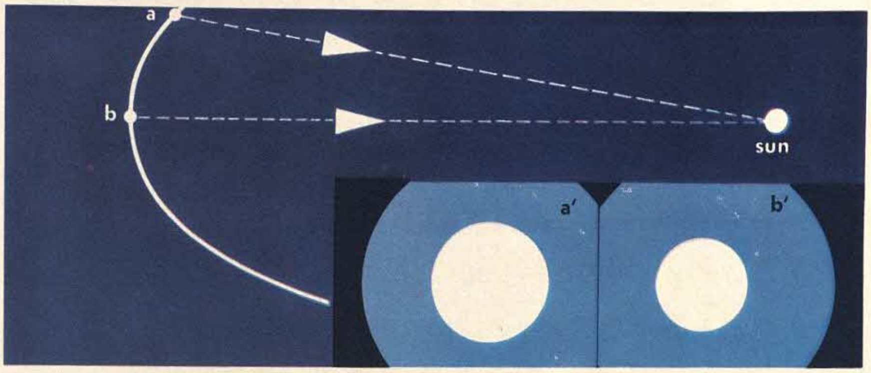


VARIATION OF THE SEMIDIAMETER—In the case of both the sun and the moon, the semidiameter varies with time. Because of the Earth's elliptical orbit around the sun, at its closest point **a** the sun appears largest **a′**, while at its furthest point **b** the sun appears smallest **b′**. Specific navigational tables give the exact semidiameters of the sun and moon for any season.

ets require corrections in their position readings, calling for time-consuming and tedious calculations.

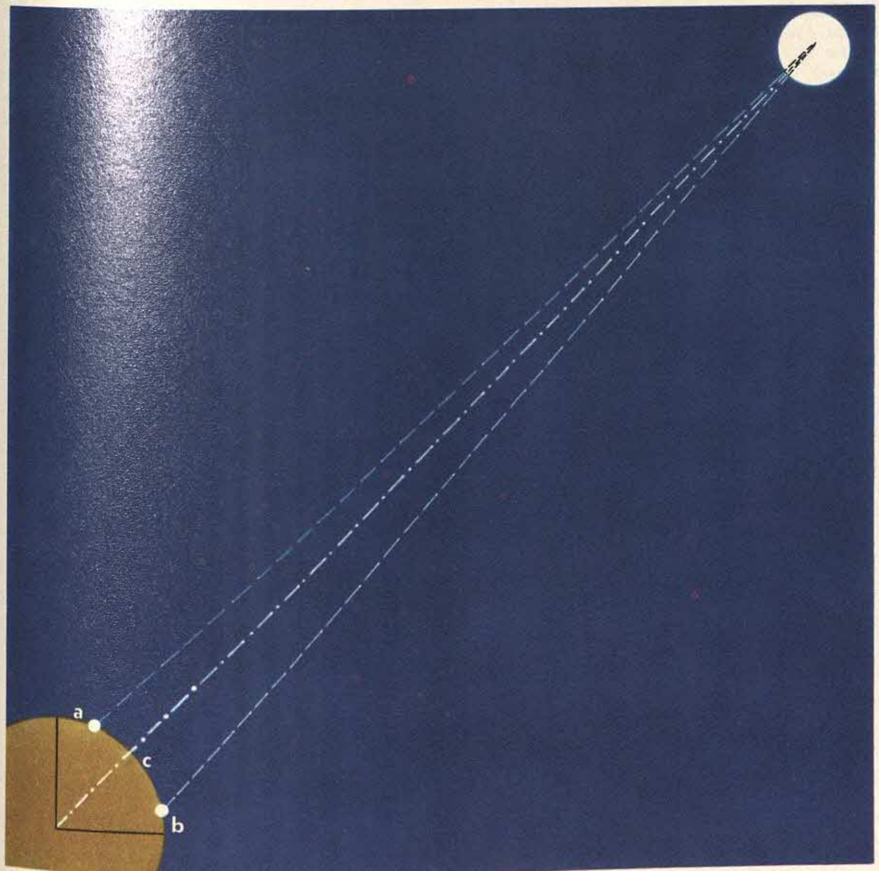
Time is an important factor during celestial observations, particularly of stars far from the meridian. It is useless to know the height of a star without knowing the exact hour, minute, and second that the height was determined. Before the invention of the naval chronometer, the only way of knowing the time at sea was to know the position of the moon. Because the moon moves rapidly, its proximity to a particular star permits the determination of the time. In the past, great importance was attached to the prediction of the moon's motion. The introduction of the chronometer was a great improvement. Large ships carried three such instruments in case one should malfunction. (With only two chronometers, it is impossible to determine which of the two is inaccurate in case of a time discrepancy between the two.

The first practical marine chronometer was invented in mid-eighteenth century by John Harrison, a self-taught British horologist. After five months at sea, one of his clocks was off by less than a minute—a better record than any clock of the time had set on land. Harrison's mechanism was complicated and costly, however. At about the same time, Pierre Le Roy, a French inventor, created and built a marine timekeeper with a mechanism that embodied in embryonic but perfectly recognizable form nearly all the essential features of the modern chronometer. Le Roy's work was extended by Ferdinand Berthoud in France and by John Arnold and Thomas Earnshaw in England. As early as 1785, Earnshaw produced several chronometers that are scarcely distinguishable from the most modern chronometer developed.

Today, radio time broadcasting has made the chronometer superfluous. A good wristwatch is sufficient for the celestial navigator, if checked before and after observations.

NORMAL PARALLAX—When a sextant is used to measure the position of the moon or a planet near the Earth, the results vary according to whether the point of observation is closer to the Poles a or the Equator **b,** or is exactly aligned with the centers of the Earth and moon **c.** Therefore, it is necessary to know the exact latitude in order to correct the sextant's reading. Such correction is unnecessary in the case of stars, which are so distant that the small change in position on Earth is unimportant.

7



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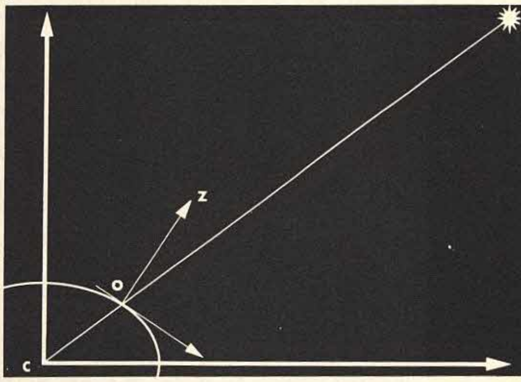
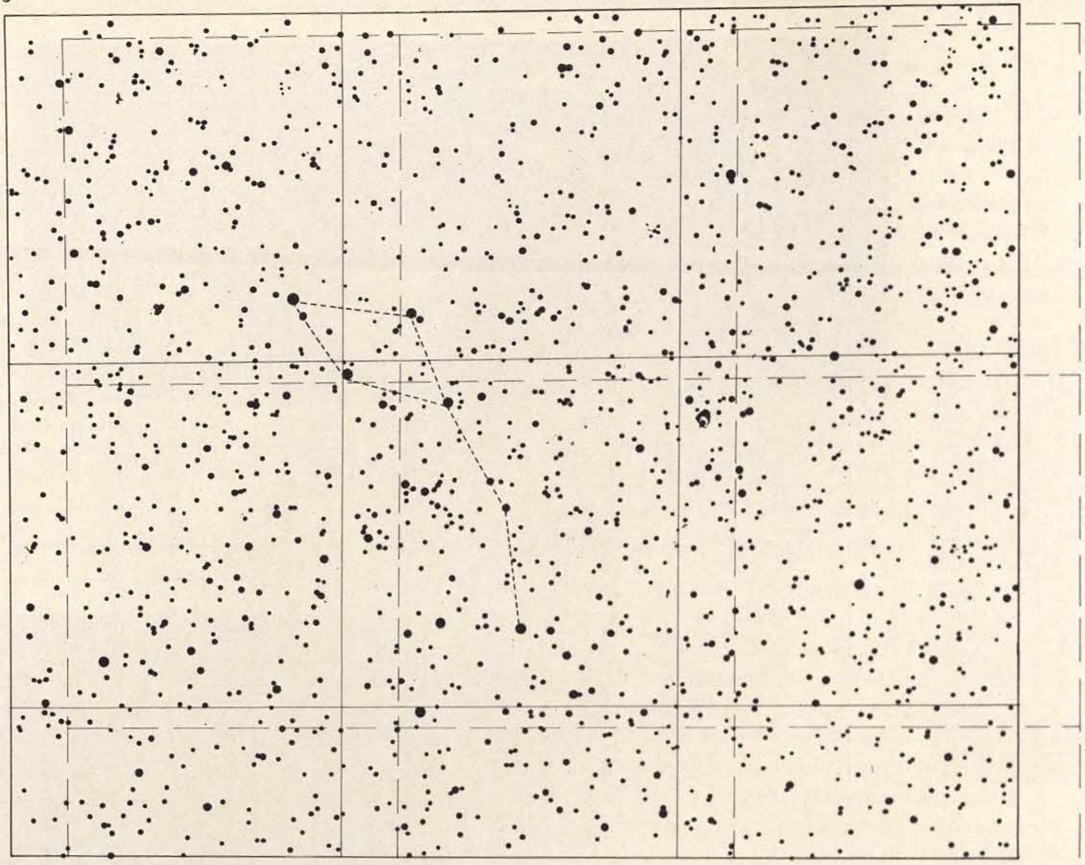


SHAPE CORRECTION—Another correction in reading elevation is necessary because the terrestrial meridians are elliptical rather than circular. The direction zenith-observer-nadir **ZO** of any point on Earth (except for the Poles and the Equator) does not point toward the center of the Earth **C** because of the elliptical meridian. Thus, the correction must be made. Despite the need for all the corrections, astronomical determination of position can be quickly calculated through the use of navigational tables in which the calculations have already been worked out.



CORRECTING FOR PRECESSION—When a star instead of a planet is used to determine a point, the phenomenon of precession becomes a factor in the calculation. This movement of the Earth's axis continually changes the position of the Poles and thus of all related coordinates. The diagram shows the positions of the celestial coordinates relating to the constellation Delphinus for the years 1950 (solid line) and 2000 (broken line).

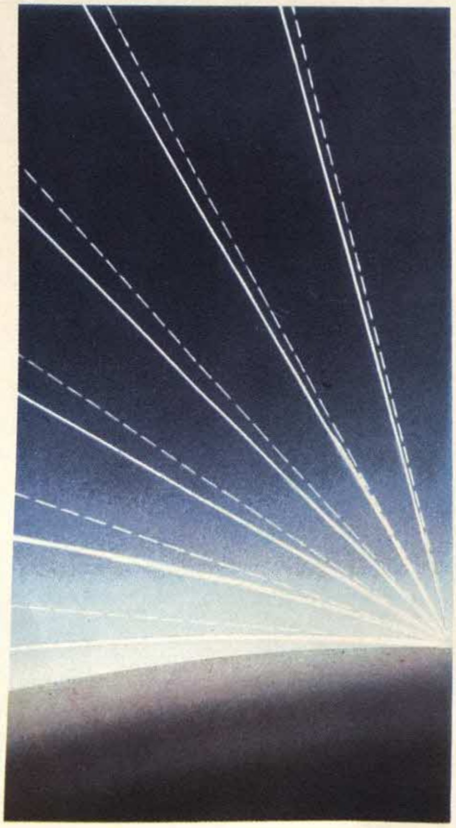
10

ATMOSPHERIC REFRACTION—After the addition of solar and lunar semidiameters, the most important correction in the measurement of elevation is necessitated by atmospheric refraction. Rays emanating from a stellar source reach the observer on Earth after passing through a layer of atmosphere. The density and amount of refraction increase with proximity to the Earth's surface. The effect of refraction is to make the rays penetrating the atmosphere bend slightly toward the vertical of the plane of observation. Thus, the rays tend to appear slightly higher above the horizon than they actually are. The amount of this discrepancy varies with the elevation of the star above the horizon. For example, a star at 80° will appear 10″ (seconds of arc) higher. Such an elevation is generally negligible in working out nautical problems. However, in stars of lesser elevation, it may be greater than one minute of arc, and in stars situated on the horizon, it is a half degree.

In this case, too, navigational tables indicate actual stellar elevations with correction for refraction to be coordinated with measured elevations.

Illustration 10a shows that rays emanating from extra-atmospheric space (solid lines) have a certain inclination with respect to the observer's horizon; as they descend toward it, they gradually curve toward the vertical. The direction in which the observer sees the star is that of the tangent with the curve of arrival of the rays, which is carried toward the observer (broken lines). The distance between the curve and the rays becomes greater in relation to the length of time the star remains on the horizon. The table (Illustration 10b) measures the quantity of atmospheric refraction under conditions of normal temperature and pressure—that is, at sea level.

a



b

AVERAGE REFRACTION

Height	Refraction	Height	Refraction	Height	Refraction
0°	34′50″	11°	4′47″7	30°	1′39″5
1°	24′22″	12°	4′24″5	35°	1′22″1
2°	18′06″	13°	4′04″4	40°	1′08″6
3°	14′13″	14°	3′47″0	45°	57″6
4°	11′37″	16°	3′18″2	50°	48″3
5°	9′45″	18°	2′55″5	55°	40″3
6°	8′23″	20°	2′37″0	60°	33″2
7°	7′19″	22°	2′21″6	65°	26″8
8°	6′29″	24°	2′08″6	70°	20″9
9°	5′49″	26°	1′57″6	80°	10″2
10°	5′16″	28°	1′48″0	90°	0″0

MEASURING ASTRONOMICAL DISTANCES

the dimensions of the universe from trigonometry

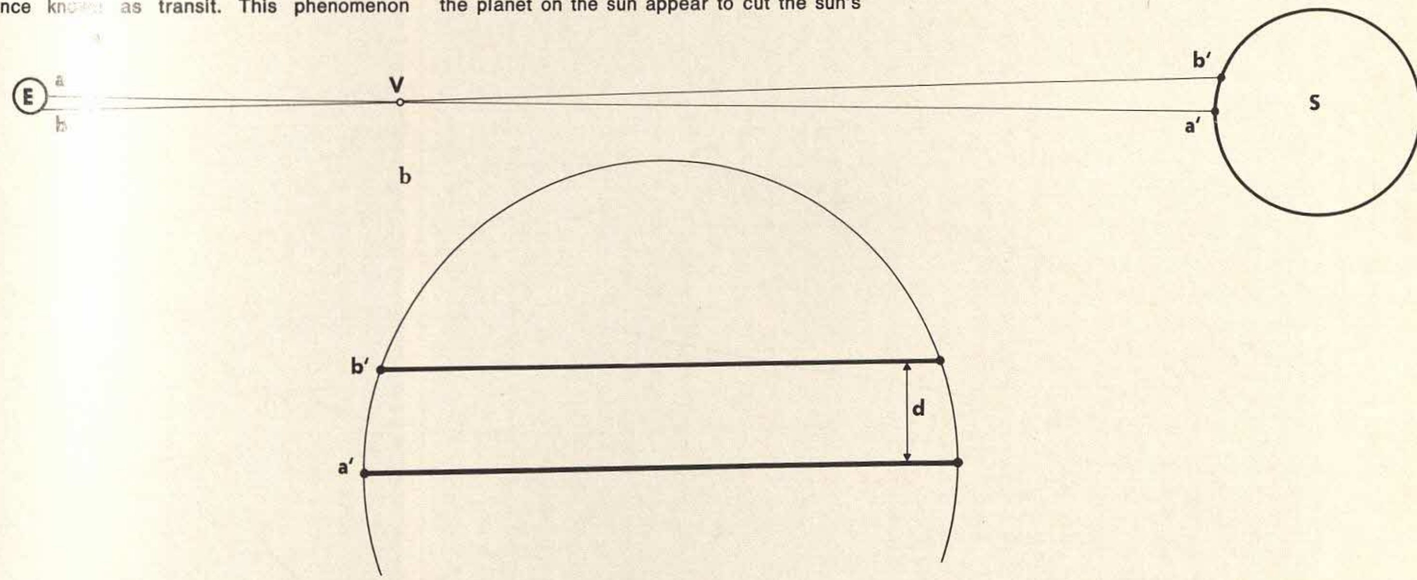
As man's knowledge of the universe has progressed, his knowledge of astronomical distances has increased in direct proportion. Had sixteenth-century scientists been able to measure the distances of the planets from the Earth, the Copernican theory could have been confirmed quickly and easily. Not until the nineteenth century could the distances of the planets be measured; for many centuries prior to that time, approximate values had been assigned to the distances of celestial bodies. These values were generally inaccurate because the planets were then believed to be quite close to

1

THE ASTRONOMICAL UNIT FROM THE PASSAGE OF VENUS—The use of triangulation from a base on the Earth to calculate the distance of the sun would yield inaccurate results because of the smallness of the angle under which the sun can be observed from the Earth. To solve this problem, astronomers have devised a system wherein a chronometer is used to transform the measurement of an angle into a measurement of time. Illustration 1a shows a principle of such measurement. Venus **V** during inferior conjunction occasionally passes in front of the sun **S,** an occurrence known as transit. This phenomenon appears in different ways when observed from two points at different latitudes on the Earth **E.**

The observer at the higher latitude **b** sees the transit taking place higher up, at **b′,** on the sun's disk than the observer at the lower latitude **a,** who sees the transit lower down at **a′**. The difference in height of the two trajectories of transit depends both on the difference in latitude of the two observation points and on the Earth-sun distance.

Illustration 1b shows a basic fact of measurement: the two trajectories of the transit of the planet on the sun appear to cut the sun's disk in two places at different heights, with the result that the phenomenon lasts different lengths of times, depending on the locations of the observation points. The length of the planet's period is determined by measuring the elapsed time between the entrance and exit of the planet on the sun's disk. From the difference between the transit times observed from the two latitudes, the distance **d** of the two passages on the solar disk can be calculated and therefore, by means of the method of triangulation shown in Illustration 3, the Earth-sun distance can be determined.



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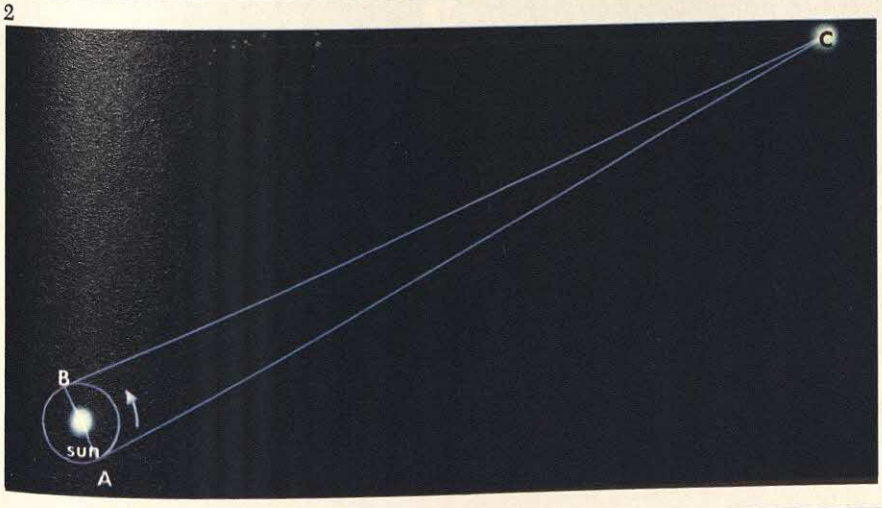
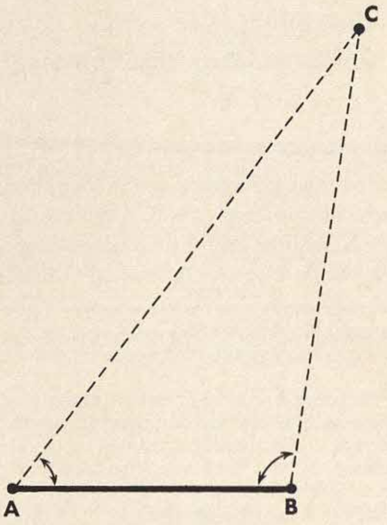


STELLAR DISTANCES—The closest stars are so far away that observation points on the Earth cannot be used to construct a triangle whose base angles are not supplementary. Therefore, it is necessary to use a larger base —that supplied by the orbit of the Earth's revolution around the sun. In one year the Earth moves from position *A* to *B*, two opposite extremes of its orbit. Since the radius of this orbit is approximately 150 million km (about 93 million mi), the base for the measurement of distances is about 300 million km—vastly larger than any base possible on the Earth, whose diameter allows a maximum base of approximately 12,700 km (about 7,900 mi). Despite the fact that the 300 million km base is more than 20,000 times greater, the distance to the nearest star is so great that the angle at the star *C* of the triangle *ABC* is only one second of arc (1/3,600 of one degree). Sensitive instruments measure such distances.

3

THE PRINCIPLE OF TRIANGULATION—The distance between an observer and an object above the Earth's surface can be measured by simple triangulation. Object *C* lies at a distance from observer *A* which must be determined. A second point *B* is located on the Earth's surface at a known distance from *A*. A theodolite is placed at *A* and fixed successively on *B* and *C*, thus measuring the angle *CAB*. The theodolite is then placed at *B* and fixed on *A* and *C*, thus measuring the angle *ABC*. Two angles and the side *AB* of the triangle *ABC* have already been determined. With these known factors and the use of a trigonometrical calculation, the distance which separates *A* from *C* can be determined. The accuracy of this method depends on the precision with which the angles at *A* and *B* and the distance *AB* are measured and on the accuracy of the measurement of the angle at *C*. If this angle is very small (which occurs if the distance from *A* to *C* is great enough), the two angles at *B* and *A* are almost supplementary, making it difficult to establish the precise measurement of *AC* or *BC*.



DISTANCES OF PLANETS—The Earth-moon distance is a very small astronomical distance. The distance of a planet from the Earth or from the sun is so much greater that its measurement by triangulation would be extremely inaccurate, if not impossible, because the angle formed by the two Earth stations with the planet would be too small. Fortunately, Kepler's laws provide a solution to the problem. Illustration 5 shows the plan of the planetary system. Next to each planetary orbit are marked the radius **r** (taking as 1 the Earth's orbit) and the time taken to complete one orbit. Kepler's third law established that the squares of the periods (the time taken to complete one orbit) of the planets are in the same proportion to one another as the cubes of half the major axes of the orbits. The semi-

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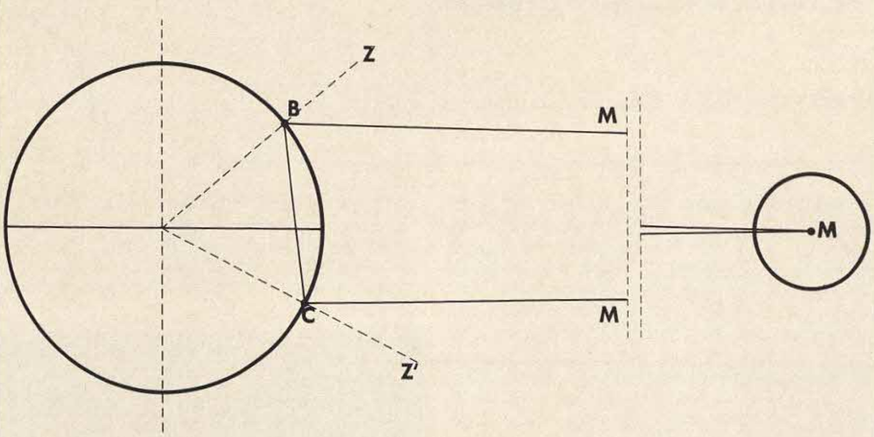
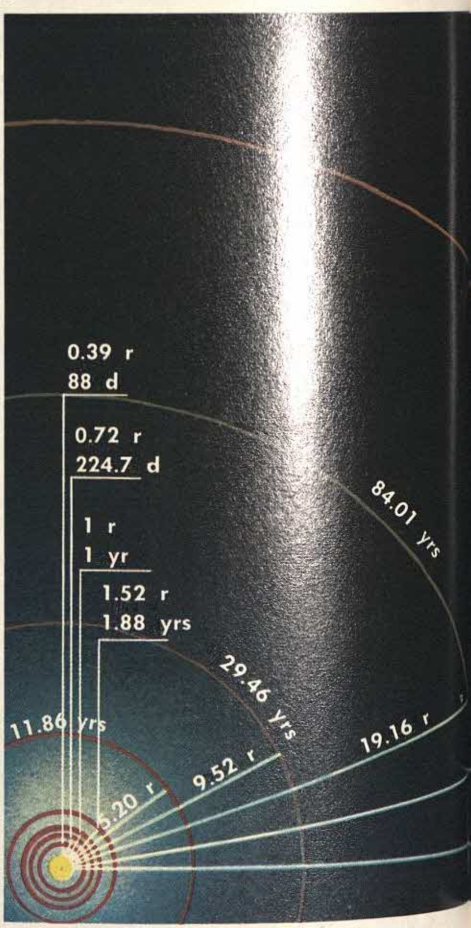


MEASUREMENT OF THE DISTANCE BETWEEN THE EARTH AND THE MOON—The distance between the Earth and the moon can be easily determined by triangulation. Two stations on the same meridian—Berlin and Cape of Good Hope, for example—observe the moon at the same time and determine its zenith-distance. From Berlin, *B*, the zenith-distance is *ZBM* (*M* is the moon); from the Cape, *C*, the distance is *ZCM*. The distance which was *AB* in Illustration 3, and which is known as the base of the triangulation, is now the segment *BC*, or the distance through the Earth between the two stations. This distance can be determined accurately once the dimensions and shape of the Earth, and the exact positions of *B* and *C* on it are known. The angles at *B* and *C* of the triangle *BCM* can be determined by the measurement of the two zenith distances. This measurement can be made, for example, with the meridian circle. The moon is so close to the Earth that the result will be a triangle with an angle *BMC* of about one degree—an angle large enough, from an astronomical viewpoint, to permit precise measurement of the moon's distance from the Earth.

The distance obtained by this measurement, however, is subject to infinite corrections, above all, correction for the fact that the distance is reckoned from the center of the Earth and not from a point on its surface. Also, the distance varies continuously because the moon revolves around the Earth elliptically.

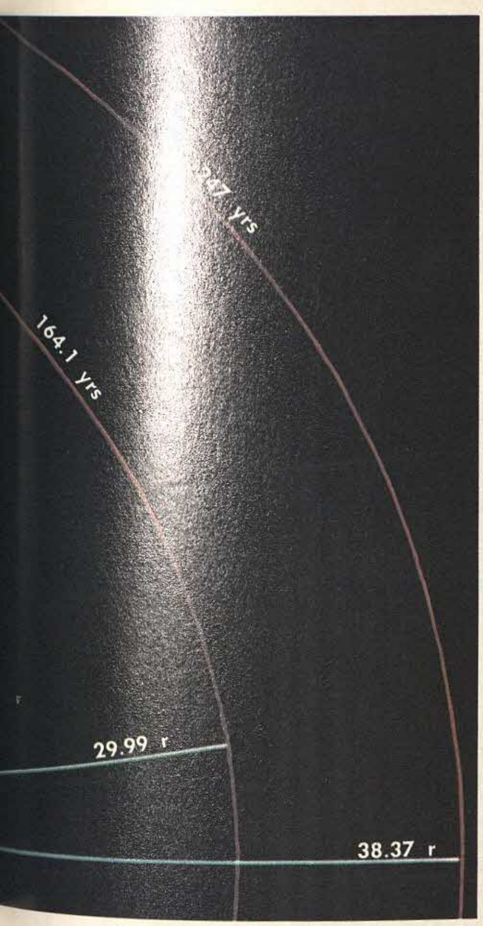
5



the Earth. Astronomical distances could be measured accurately only when precision distance-measuring instruments were developed–and the first of these did not appear until the end of the eighteenth century.

In terms of astronomical distance, that between the Earth and the moon is infinitesimal. It can be measured by the same method, based on triangulation, that is used to measure topographical reliefs (see Illustration 3). This method can also be adapted to measuring the smaller distances within the solar system; and, with some variations, it can be applied as well to the measurement of the distances of the nearer stars. But for greater distances, indirect calculation major axes have been approximately determined as radii of circles which most closely resemble the orbits. The periods can be established easily enough. Once the period of the Earth's orbit has been established (one year) and that of another planet, the relation between the diameters (or the radii or the major axes) of the two orbits can be determined. The time taken to complete the orbits and the relationship of the diameters of these orbits provide one of the most accurate measurements carried out in astronomy. If at any moment the precise Earth-Mars distance is known, for example, the dimensions of the other planetary orbits can be determined.

Two distances within the solar system are easy to measure—the Earth-sun distance and that between the Earth and an asteroid.



THE ASTRONOMICAL UNIT BY MEANS OF AN ASTEROID—This illustration outlines the principle of measurement of the astronomical unit by means of an asteroid. **E** is the orbit of the Earth and **A** the orbit of an asteroid. During their orbits the two bodies approach each other closely enough so that the distance between them is minimal. The Earth-asteroid distance is measured by triangulation carried out from a base on Earth. This measurement gives the difference in dimensions between the major axes of the two orbits, while the relationship of the periods of the two bodies gives the relationship of the dimensions of the major axes. These two statements are expressed mathematically by a system of two equations and two unknowns, which, when resolved, furnish the elements of the problem. As the asteroid passes close to the Earth, an accurate measurement of the difference and a perfect measurement of the Earth's orbit can be made.

Over a period of a century more than one asteroid will pass close to the Earth at a distance only a few times greater than that of the moon. Each time, astronomers measure, with ever more accurate methods, the distance between the Earth and the asteroid. From these measurements, determination of the Earth-sun distance is carried out with ever greater precision. Since the Earth-sun distance serves as the unit by which all planetary distances are measured, it is known as the astronomical unit. This unit is even more useful as the unit of measurement for stellar distances.

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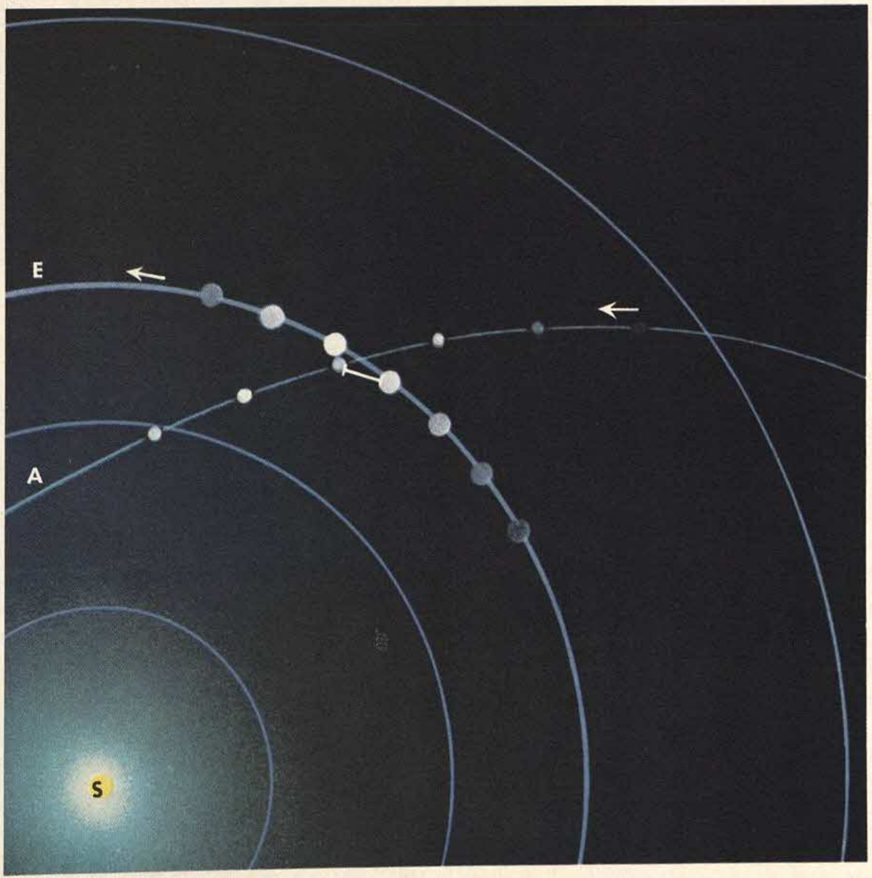

must be used. Information of this kind is of the greatest importance, because knowledge of the dimensions and distribution of celestial bodies in the universe depends on our knowing, in turn, exactly how far we are from those bodies.

After World War II, radar astronomy—the study, by means of radio reflection, of the moon and other bodies in the solar system—became possible through increased transmitter power, greater receiver sensitivity, and the use of electronic computers to discriminate between the extremely weak echo signals and the stronger interfering signals of radio noise. The radar technique allows more accurate measurement of distances than optical methods permit, and it enables study of the surface structure of bodies in the solar system.

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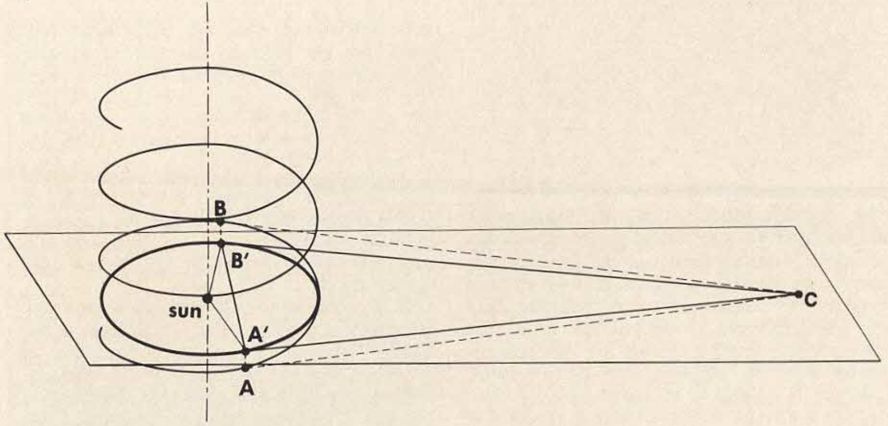

THE TRUE TRIANGLE—Measurement of the Earth-sun distance is made under different conditions from the ideal ones in Illustration 2. The Earth is in two different positions from those at the extremes of a diameter perpendicular to the distance of the star *C*. In most cases the Earth is at points *A′* and *B′*. Because the measurement of the star's position cannot always be made at the ideal time (due to weather or other circumstances), the base is not equal to the diameter of the Earth's orbit, but may be equal to the length of the segment *A′B′*. The base of the triangulation is further compromised by the fact that it is not perfectly straight as is the perpendicular to the star. These are the principal circumstances taken into account in measuring the distance of a star.

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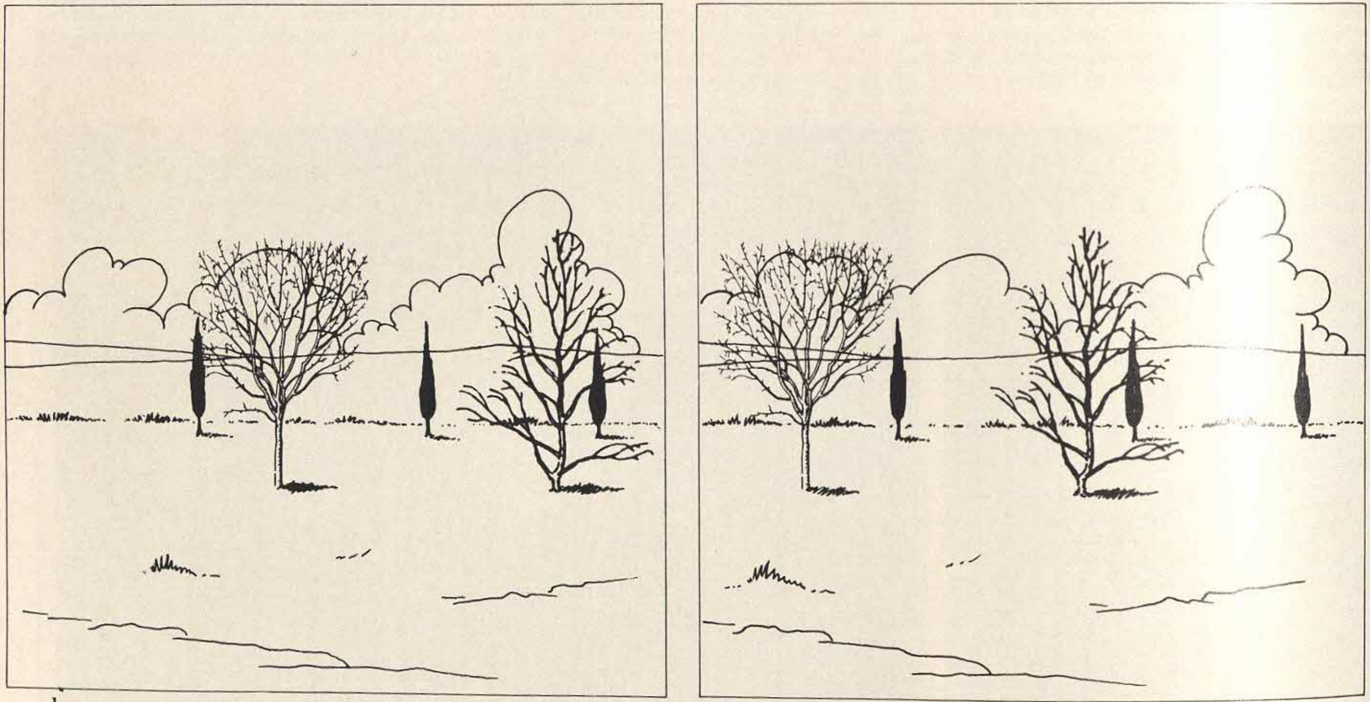

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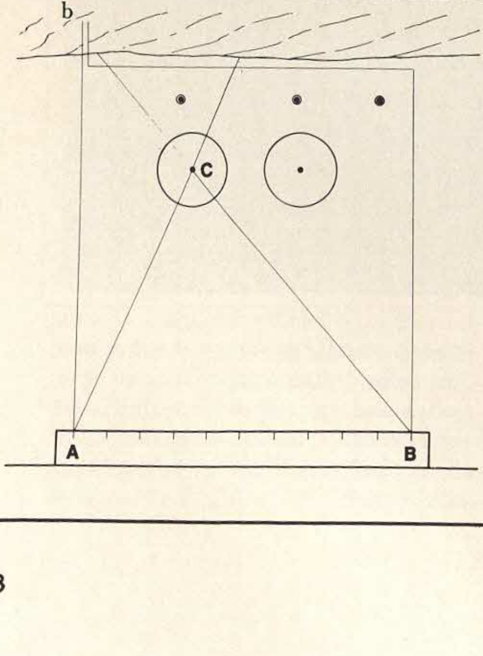

THE PRINCIPLE OF PARALLAX—The measurement of the small angle at the vertex of the triangle—the angle used to determine the stellar distance—is carried out using the principle shown by Illustration 8. Each of the two frames has hills on the horizon; in the distant foreground are three cypresses and in the near foreground two other trees. An observer is looking at the scene from the windows of a house. If the observer looks from a window on the left and then from one on the right, he will notice no difference in the position of the hills: they will appear the same because of their great distance. Looking from the window on the right and then from that on the left, however, one of the closer trees will seem to be displaced to the right. From a window on the right, the tree will seem to be displaced to the left. Illustration 8b shows how this principle of the displacement of objects allows triangulation. If an observer moves along the front of the house, observing an object placed at a great distance, he always sees it in the same direction. Two points of observation are represented by *A* and *B*. If the observer sees the tree along the line *BC*, it appears displaced to the left; if it is seen along the line *AC*, it appears displaced to the right. Half the angle at *C* is known as the parallax of the object.

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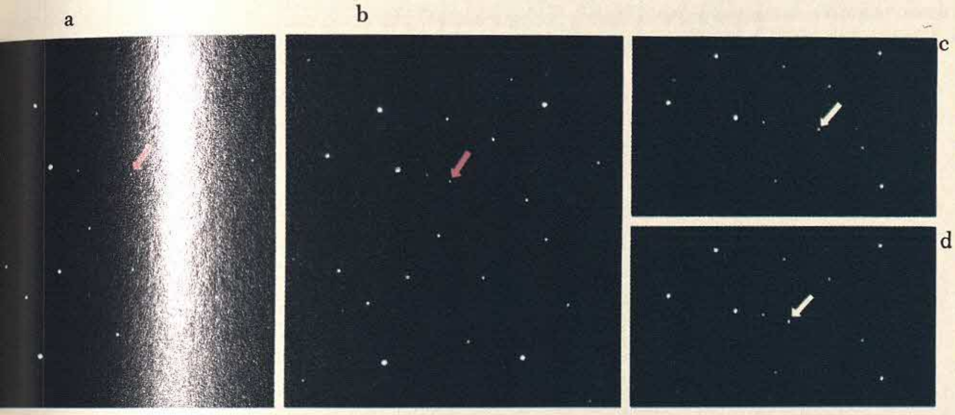

PARALLAX OF STARS—A method based on photography is used to measure the parallax of a star. If the field of the sky containing the star is photographed at a six-month interval, a pair of photographs result in which all the stars of the field are seen in exactly the same position, while the particular star appears to be in slightly different positions (Illustrations 9a and 9b). Illustrations 9c and 9d show the extent of the movement of the star (about 0.25 seconds of arc). The illustrations correspond to photographs taken with a telescope having a focal length of at least 10 m (about 400 in.). A displacement in stellar position of one second of arc is represented on such photographs by a difference in position of 0.05 mm. Sensitive instruments can determine the position of the star with an accuracy of 0.0001 mm; consequently, the parallax of a star can be determined to within one-fiftieth of a second of arc.

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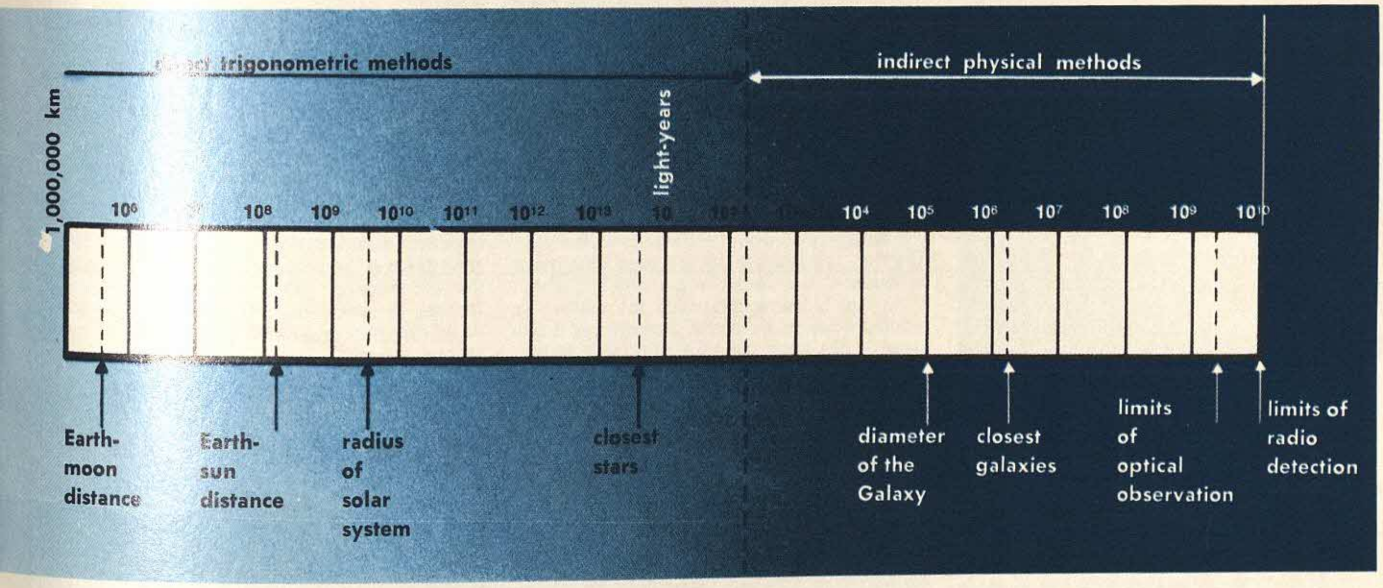


THE LIGHT-YEAR, THE PARSEC, AND TRIANGULATION OF THE UNIVERSE—Distances within the solar system are small enough to be expressed and understood in kilometers or miles. The furthest planet, Pluto, is a little less than 6 billion km (about 3.7 billion mi) from the sun, while the nearest, Mercury, is about 58 million km (about 36 million mi). However, the use of kilometers or miles to express the distance of the closest star is as awkward as expressing distances on the Earth's surface in microns. Therefore, a much larger unit of measure—the light-year—is used. This unit is the distance light travels in one year: 9,460,000,000,000 km (about 6 trillion mi). A more natural unit of measure is the parsec, which corresponds to the distance of a star whose angle of parallax subtended by the radius of the Earth's orbit (also called astronomical unit) is one second of arc. Astronomers frequently use the parsec as a unit of measure for stellar distances. This distance corresponds to 3.26 light-years and is equal to 30.87 trillion km (about 19 trillion mi). It is extremely difficult to measure the distance of any star because of the smallness of the angle of parallax. For stars having a parallax equal to about 0.04—about 80 light-years in distance—the parallaxes, and therefore the distances, can be measured to an accuracy of 10 percent. Distances of up to 200 light-years can still be determined with fair accuracy; greater distances can be determined only with much higher error factors. Beyond 300 light-years the trigonometric method fails completely. The most distant celestial objects visible through a telescope are about ten million times further away than stars that are 300 light-years distant. Illustration 10 shows the practical limits of trigonometric distance determination and shows how this method is limited to celestial bodies close to the planetary system.

MEASURING GREAT ASTRONOMICAL DISTANCES

a yardstick for infinity

Theories about the structure of the universe survive or fall by the measurement of astronomical distances. It is amazing that, when the Ptolemaic theory of cosmology was abandoned in favor of the Copernican theory, it had not yet been established how far the celestial bodies these theories dealt with were from Earth. Although the ancient Greeks had made estimates of the distance to the sun and moon, in Galileo's time, and even in Newton's time, astronomers did not know the distances of the heavenly bodies, not even approximately.

The problem was gradually solved. Astronomers first learned how to measure the lesser astronomical distances—those within the limits of the solar (or planetary) system. The first distance to be measured was that of the moon, followed by those of the planets and the sun. The distance of the sun, known as the astronomical unit, is in fact basic for astronomical measurements, inasmuch as the distances of the planets can be deduced by means of Kepler's harmonic law; this law makes it possible to establish the relationship between the size of the planets' orbits, if the period of these orbits is known—and if the period of these orbits is easily measurable.

THE FIRST STEP AND THE BASIC UNIT—The distance from the Earth to a planet, such as Mars (above), can be found by triangulation; this system also can be used to measure the distance to the sun or to a minor planet, such as Eros or Icarus, that comes near the Earth. The minimum distance involved is of the order of millions of miles, and therefore the base on Earth on which the distance is to be triangulated is many times smaller than the distance itself.

In calculating a distance, some error is inevitable, but its size depends on the distance involved. What would be considered a gross error in a triangulation measured on the Earth's surface would be considered very precise measurement in calculating the distance of celestial bodies. Indeed, no other method of determining distance can be more precise. All planetary distances do have some margin of error, but the degree of approximation must be considered very close. To calculate the basic distance between the Earth and the sun, for example, the method of triangulation can be checked by other methods, such as the passage of Venus or Eros across the face of the sun. The minimum, mean, and maximum distances between the sun and the Earth can be stated approximately, in millions of miles, as 91.3, 93, and 94.5 respectively.

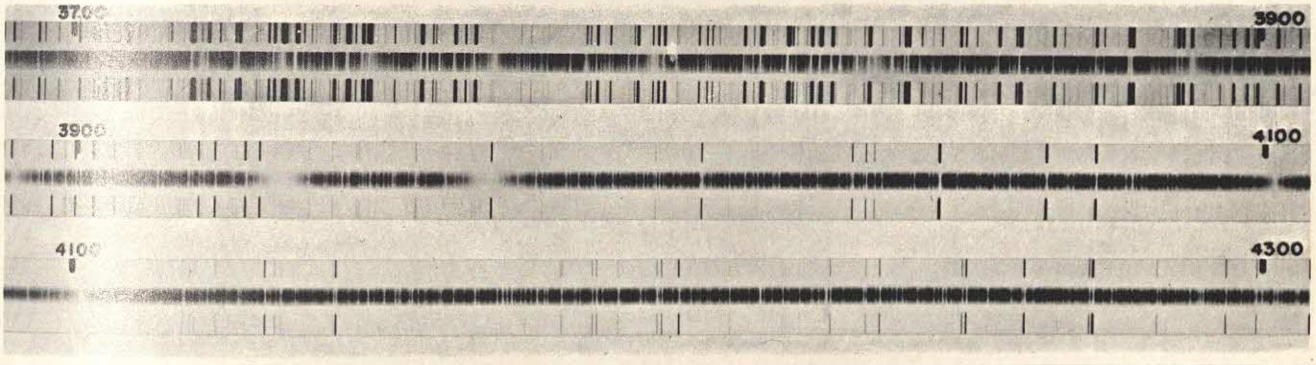
THE SECOND STEP: MEASURING THE PARALLAXES OF THE STARS—The second step is the determination of the distances to the stars relatively near the Earth. Friedrich Wilhelm Bessel showed the way to use trigonometry to determine the distance of many of these stars.

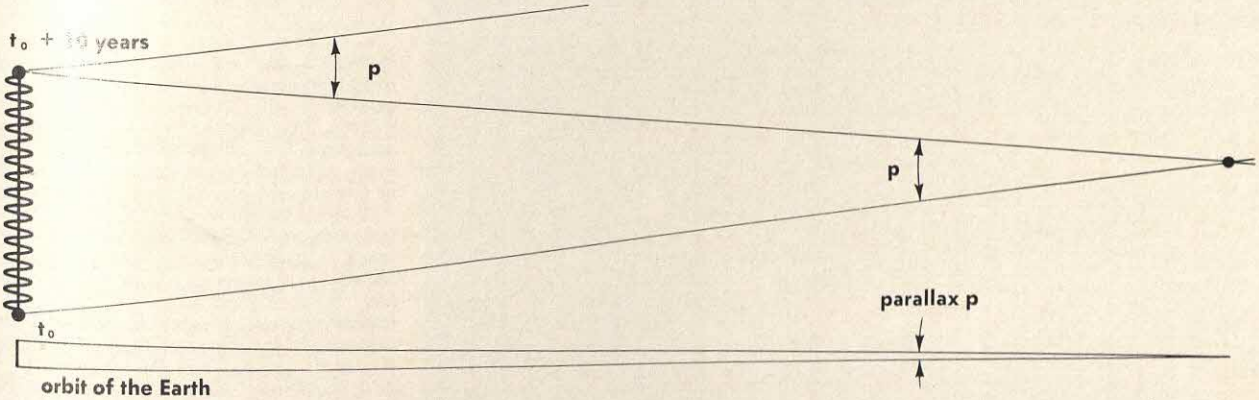
The base for the triangulation in calculating such distances is the diameter of the Earth's orbit. The parallax of a star is one half the angle subtended by this diameter at the star. It is simply related to the distance to the star. However, the triangle on this base must have an angle at the vertex in the order of about 1″ to 0.01″; below this value the method is too imprecise to be useful. However, in some cases it has been used for parallaxes of less than 0.01″. Below that limit the degree of imprecision of measurement rises from a few units per hundred to some tens per hundred, beyond which measurement is useless. Only a few thousand stars can be measured by trigonometric parallax. When this method is applied to measuring the distances to stars, it is far less precise than when used to measure the distance from the Earth to the sun. However, even if no error of this kind existed, some imprecision would arise because of the imperfect knowledge of the astronomical unit. Nevertheless, some validity remains in using the astronomical unit to refer to stellar distances, for each further improvement leads to an ever-improving knowledge of stellar distances.

SPECTROSCOPIC PARALLAXES—From a stellar spectrum such as this spectrum of Alpha Cephei, it is possible to determine the spectral type with great precision—that is, to locate the star on the spectrum-luminosity diagram. The position of a star on this diagram, of course, indicates with exactitude the absolute luminosity of the star (designated by its absolute magnitude). If a star has the same spectrum as the sun, for example, it also has the same absolute magnitude, 4.8 (equivalent to the apparent magnitude of 5 at the standard distance of 10 parsecs). Therefore, if the apparent luminosity or magnitude of a star is known—and this can easily be determined by using a photoelectric photometer or from a photograph—the distance of the star can be calculated.

This method of determining distance is called spectroscopic parallax, because the distance, and hence the parallax, of the star is arrived at by using the spectrum. But this method is subject to possible error; for example, it is relatively easy to discover the type of star from the presence and intensity of certain lines on the stellar spectrum—such as intense hydrogen lines, which signify A-type stars with strong absolute luminosity, or molecular lines and bands that signify older stars with weak absolute luminosity—but the distance calculation may be erroneous for two reasons. First, there is a range of luminosity for any spectral type. Second, the appearance of the lines can easily be misconstrued, because the difference between the spectra of a giant and a dwarf star is slight. A mistake in classification can cause significant error.

In order to calculate the parallax from the spectrum, the spectrum of the star in question must be quite clear, to avoid these errors. This is possible even for very distant stars; for those in the main sequence, it is acceptable to assign distances of the order of 10,000 light-years. The possible error is obviously greater than would obtain with the use of trigonometry, but it can be limited to one fifth to one tenth of the distance covered, a distance that is to be described in terms of an order of magnitude. In point of fact, comparisons between spectroscopic and trigonometric parallaxes, where possible, have given excellent results; discrepancies between the values of the two parallaxes have been rare. It must be remembered that the spectroscopic method is less accurate than the trigonometric if the parallax exceeds 0.05″ (corresponding to a distance of 500 parsecs); but if the parallax is smaller (the distance greater), as it will be in most instances, the spectroscopic method is more accurate. It must be stressed, however, that this method depends for its validity on the construction of a perfect spectrum-luminosity diagram for all the stars for which a parallax has been determined by the trigonometric method. It follows that whatever improvement is possible in the measurement of trigonometric parallaxes will also improve the measurement of spectroscopic parallaxes.



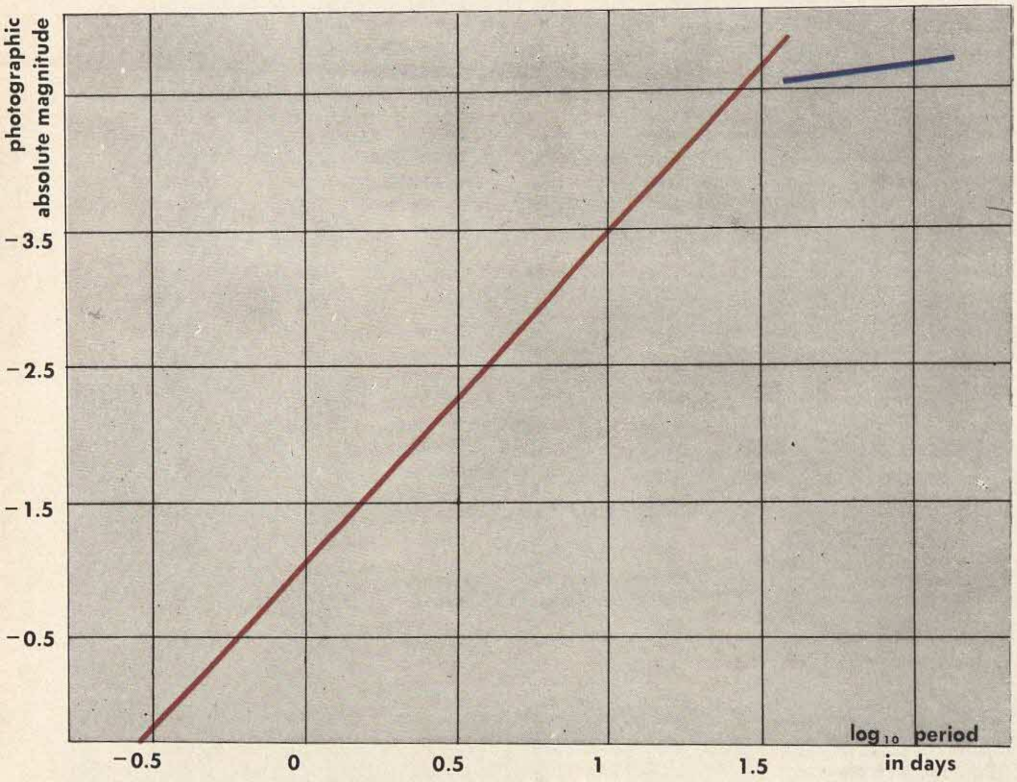


MEASURING BY SECULAR PARALLAX—It is known that the stars are not fixed in space, but move on trajectories of their own. Astronomers have also determined that the solar system moves among the stars at a velocity of about 20 km (12.5 mi) per second, in the direction of the constellation Hercules. Because of this movement, the stars around the solar system appear to move in the opposite direction at the same velocity, just as trees along the side of the road appear to move as one rides by. Just as the nearest trees seem to move more rapidly than the farther ones, so the stars that appear to move more quickly are less distant from the solar system than the stars that appear to move more slowly.

This motion of the stars is apparent within the span of a few years; during this period of time the stars seem to change their positions, and according to the greater or lesser extent of their apparent change of place it is possible to deduce their relative distance. This method makes it possible to measure the distance of many stars for which the trigonometric parallax cannot be taken because the diameter of the Earth's orbit, which is the basis for the calculation, is relatively too small. The diagram shows the path of the Earth with the sun in interstellar space. After ten years the Earth has traveled over a much longer base than that covering the span of a single orbit; therefore, the star will appear to be greatly displaced from its initial position. In this case it would be impossible to determine the distance without first deducing the velocity of the Earth in space—a calculation that, in turn, depends on the method of trigonometric parallaxes. The moon, closest celestial body, was the first to have its parallax determined.

MEASURING BY THE VARIABLES—This diagram illustrates the period-luminosity relationship for Cepheid variables and R R Lyrae stars. The red line represents the Cepheids, the blue line the R R Lyrae stars. These stars serve to measure indirectly the distance of a celestial body. The light curve of a Cepheid is distinctive and easily recognized. It is only necessary to identify the presence of a Cepheid within a star cluster or some other celestial system and to measure its period of variation to be able to establish immediately that its absolute luminosity has a specific value. The distance of the Cepheids is the distance corresponding to the value of the apparent luminosity determined by normal methods of measurement. The method of measuring by the Cepheid variables, or the cluster variables, the R R Lyrae stars, also depends on a measurement of the trigonometric parallaxes taken on some stars of the same type that are within measuring distance. This method, it must be noted, can be used up to the distances at which the apparent luminosity and variations of a star can be observed and measured with some precision. This method can be used for much greater distances than can the spectroscopic method.

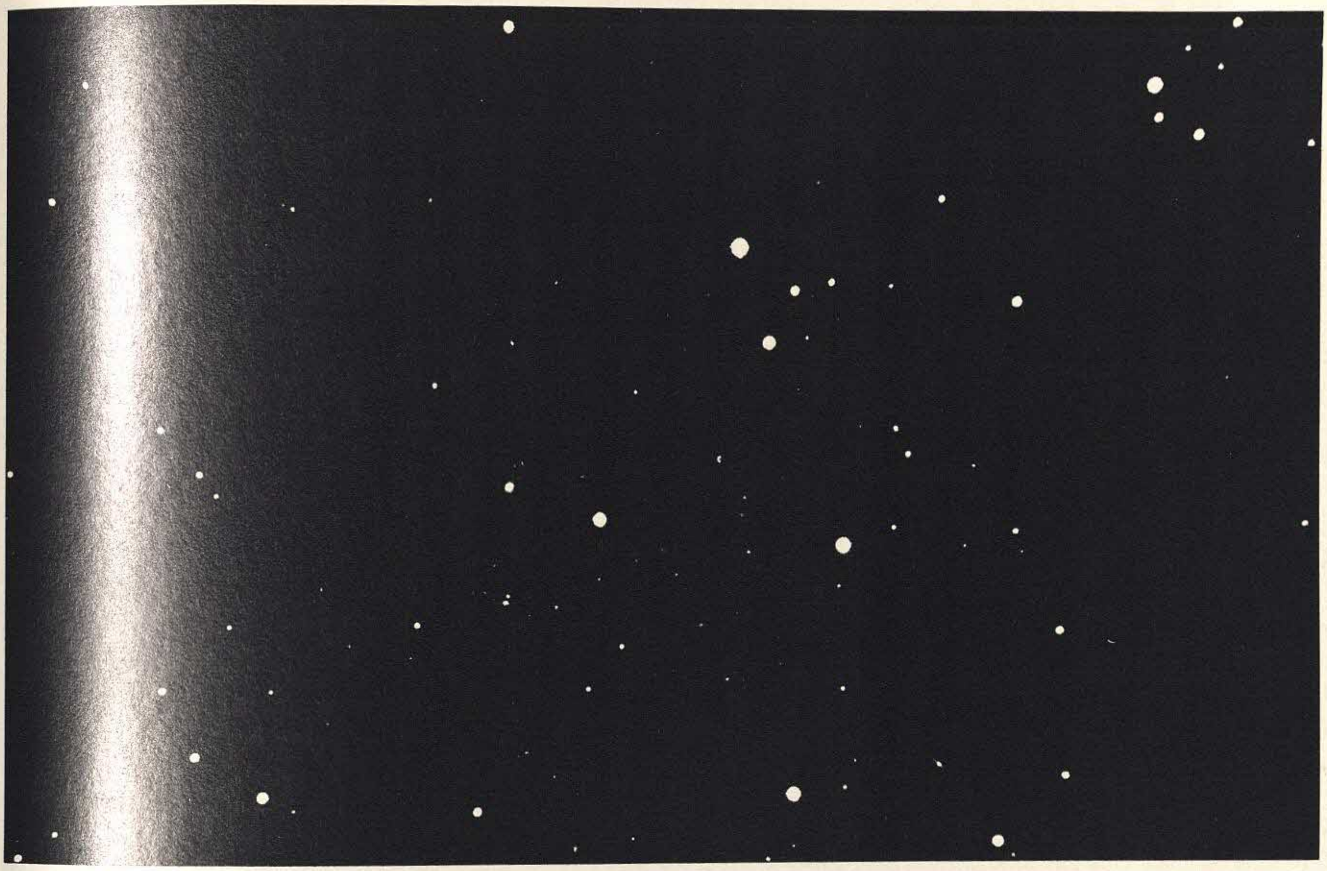
The method of measuring by Cepheids or other variable stars can determine the distance of globular clusters, open (or galactic) clusters, star clouds, and nearby galaxies. Until a few decades ago, the distance of the Andromeda galaxy was underestimated by half because of an erroneous interpretation of the type of the variables observed within it; astronomers now believe that its distance can be estimated with an error of no more than 10 or 20 percent. By using the method of measuring by the variables, it is possible to estimate distances of up to about 10 million light-years.



HUBBLE'S LAW—An important law was derived from the study of the spectra of external galaxies by the American astronomer Edwin Hubble. This law, known as Hubble's law, postulates that all galaxies recede at a velocity indicated by the Doppler effect, a shift of lines toward the red end of the spectrum.

It cannot be affirmed with certainty that this law of the recession of galaxies is valid, inasmuch as it is not known whether light, as it travels for millions of years through space, has not undergone a process analogous to friction that would cause an alteration of its wavelength. In any case, insofar as the distances of galaxies can be measured by the period-luminosity relationship of the variables, the relationship is verified; it has, therefore, been extended to the higher values of the velocity of recession.

If the relationship between the velocity of recession and distance is known, it is then possible to determine the distance of galaxies as long as their spectra can be measured—a distance of hundreds of millions of light-years.



THE GREATEST OPTICAL DISTANCES—When the spectrum of a galaxy cannot be measured, the only possible method of determining the distance of the galaxy is the method of integral magnitudes. It is known that most bright galaxies are composed of some 100 billion stars, and the stars in each galaxy have the same average luminosity, estimated at an absolute magnitude of 5. The total or integral luminosity of any bright galaxy, therefore, is about the same as that of any other such galaxy.

In order to deduce the distance of the galaxy, it is thus sufficient to observe the apparent luminosity of that galaxy, inasmuch as the absolute luminosity is taken as identical for them all. Galaxies such as those shown in this photograph are among the most distant that can be observed by using an optical telescope. Their distance is estimated, rather than measured, by their integral magnitude—in this instance, the 23d magnitude. Given their composition of about 100 billion stars with average absolute magnitude of 5, it can be deduced that their distance is between one and two billion light-years. In these cases, an error of a multiple factor of two is acceptable; although relatively imprecise, in this order of distance it can be considered reasonably precise.

The measure of the astronomical unit, as previously shown, is direct in the sense that it is a triangulation, that is, a trigonometric calculation. Here other methods of measuring astronomical distances, especially the larger ones, up to the known limits of the universe, are discussed; and it will be evident that, as the units of measurement increase in magnitude, they decrease in precision.

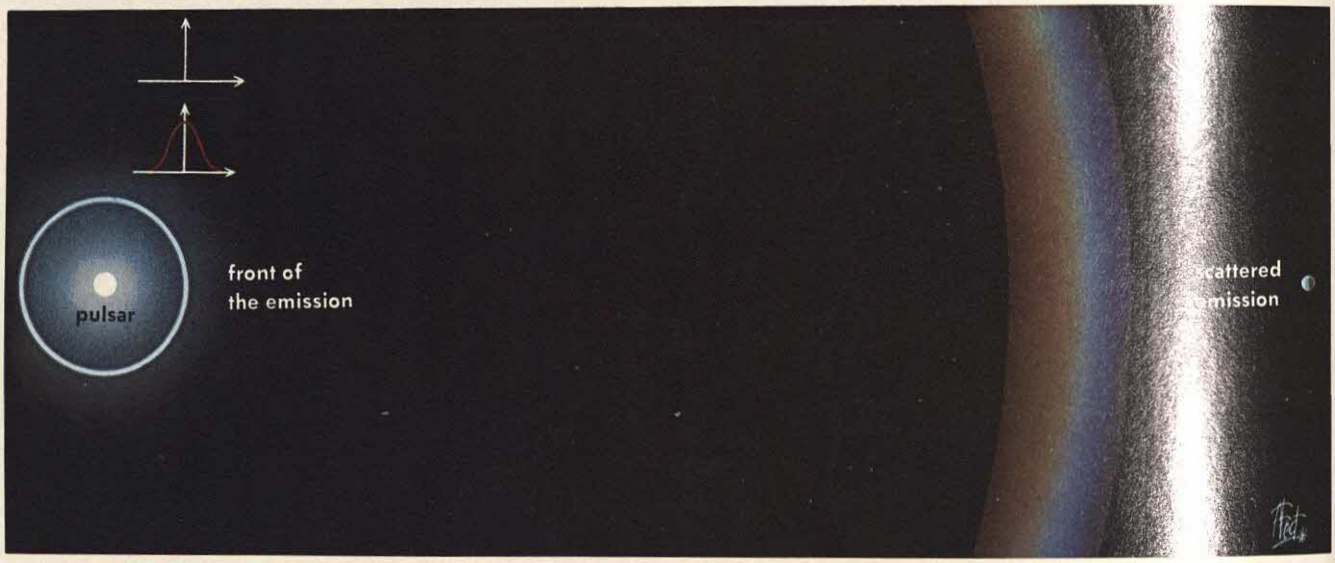
Astronomical distances include a vast range of values. A logarithmic scale would be needed to express them all at the same time; it would be impossible to plot on one linear scale all the distances, from the smallest to the largest. Except for the distances of the artificial satellites, the smallest is that from the Earth to the moon—a mean distance of 238,855 miles. Inasmuch as many later calculations of distance will be in terms of the light-year (the distance light travels in one year), and inasmuch as a light-year equals 5,880 billion miles, it is useful to express the distance of the moon in comparable terms: 0.238,855 billion miles. The distances of stars visible to the naked eye vary from a few light-years to some thousands of light-years. Scientists have been able, by using telescopes or other devices, to explore the universe to a distance of billions of light-years. The range of astronomical distances extends, therefore, from about 1/25 to billions of light-years.

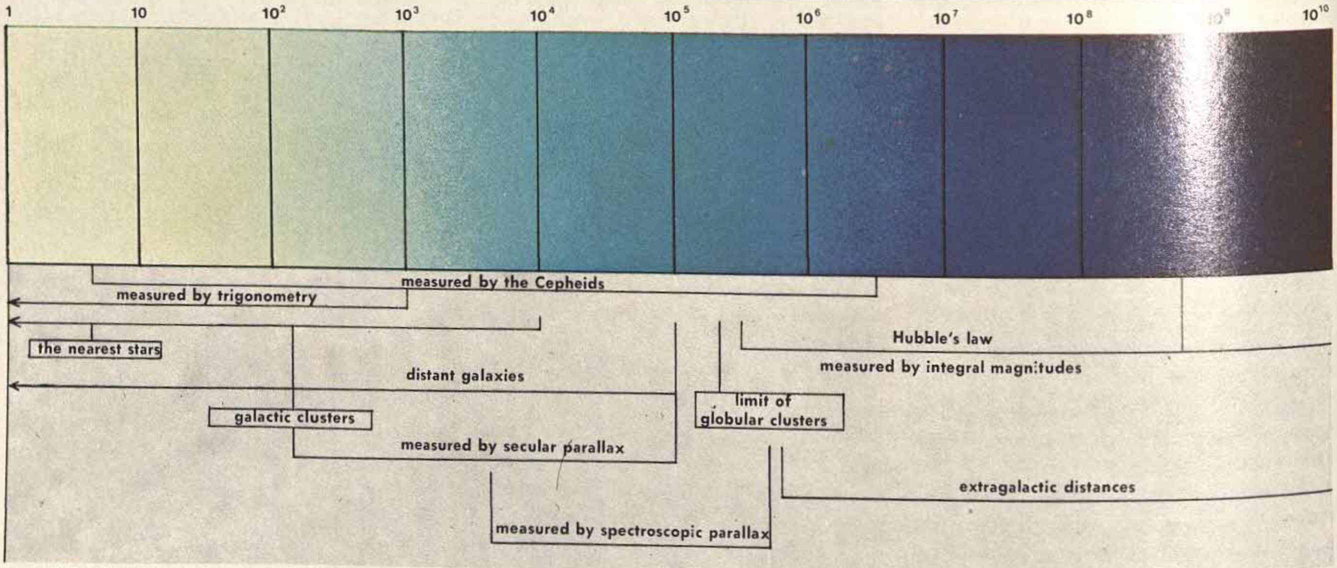
In such an enormous range of distances, it should be obvious that the order of magnitude is more important, in a given calculation, than the precise measurement. For example, if the object to be measured is a galaxy hundreds of millions of light-years distant, an error of 50 percent is acceptable; but such an error would not be acceptable in measuring the distance to the moon.

In recent years the problem has developed of determining the distance of objects that are perceptible only because of the radio waves they emit. The distance of such objects cannot be determined by any means available to optical astronomy; moreover, special systems must be adapted to cope with particular problems of this kind.

THE DISTANCES OF PULSARS—Pulsars are stars that have the characteristic of emitting radio waves—only one has been observed optically—at an extremely constant rate, at least as constant as the best atomic chronometers. Because their emission pulsates, they have been given the name of pulsars.

The distance of most pulsars is determined solely by electronic methods. Interstellar space is not a vacuum; it contains isolated electrical charges that impart to space an index of refraction of a different value than it would have if it were a vacuum. Since this is so, the waves vary in their velocity according to their frequency; radio waves emitted simultaneously in a brief impulse but with different frequencies are detected separately because they have different velocities, however minute the difference may be. The interval in the detection of the different frequencies makes it possible to deduce the time passed by the radiation between emission and detection. Because the waves travel with the velocity of light, it is possible to deduce the distance of the source.





A LONG CHAIN—Astronomical distances extend over such a wide range that they cannot all be measured by a single method. However, astrophysical studies provided methods applicable to the greatest distances. The base for all measurements is the distance between the Earth and the sun, known as the astronomical unit, and determined to a precision of about 1 percent. The next level is that of distances of the stars, determined by trigonometry with possible errors of the order of 1 percent to 10 percent. Finally, greater distances require indirect methods discussed above, in which the margin of error may have a factor of two. However, considering the difficult conditions involved in measuring the distances of the more remote stars of the galactic system, this margin must be considered acceptable.

DIFFUSE STELLAR OBJECTS | nebulas and stellar clusters

Man in his solar system is a minute part of a huge, revolving disk of stars, gas, and dust 100,000 light-years wide. This disk is the Milky Way, sometimes called the Galaxy. Looking into the confusion of the Milky Way on a clear night, an observer can see misty, cloudlike patches of light that seem to glow. These are either nebulas or stellar clusters, two of the most interesting phenomena of the night sky.

NEBULAS AND CLUSTERS

To ancient astronomers, the stars were luminous points that gave the impression that the celestial vault was rotating. Planets were generally much brighter than stars, and moved among them in definite patterns. Against the dark background of the sky, other celestial objects appeared as weakly luminous patches with vague and irregular outlines, resembling clouds faintly illuminated by the moon. Such a patch was called a nebula, from the Latin and Greek words for *vapor* and *cloud.*

With the invention of the telescope, it became apparent that two basically different phenomena had been known by the same name, nebulas. Those objects called nebulas today were seen to consist of fluorescent gaseous matter; others were seen to consist of tens of thousands of tightly packed stars. Today these latter objects are known as open clusters, globular clusters, or extragalactic nebulas (external galaxies), depending on their exact nature.

The illustrations in this article show various types of celestial objects having a nebular appearance.

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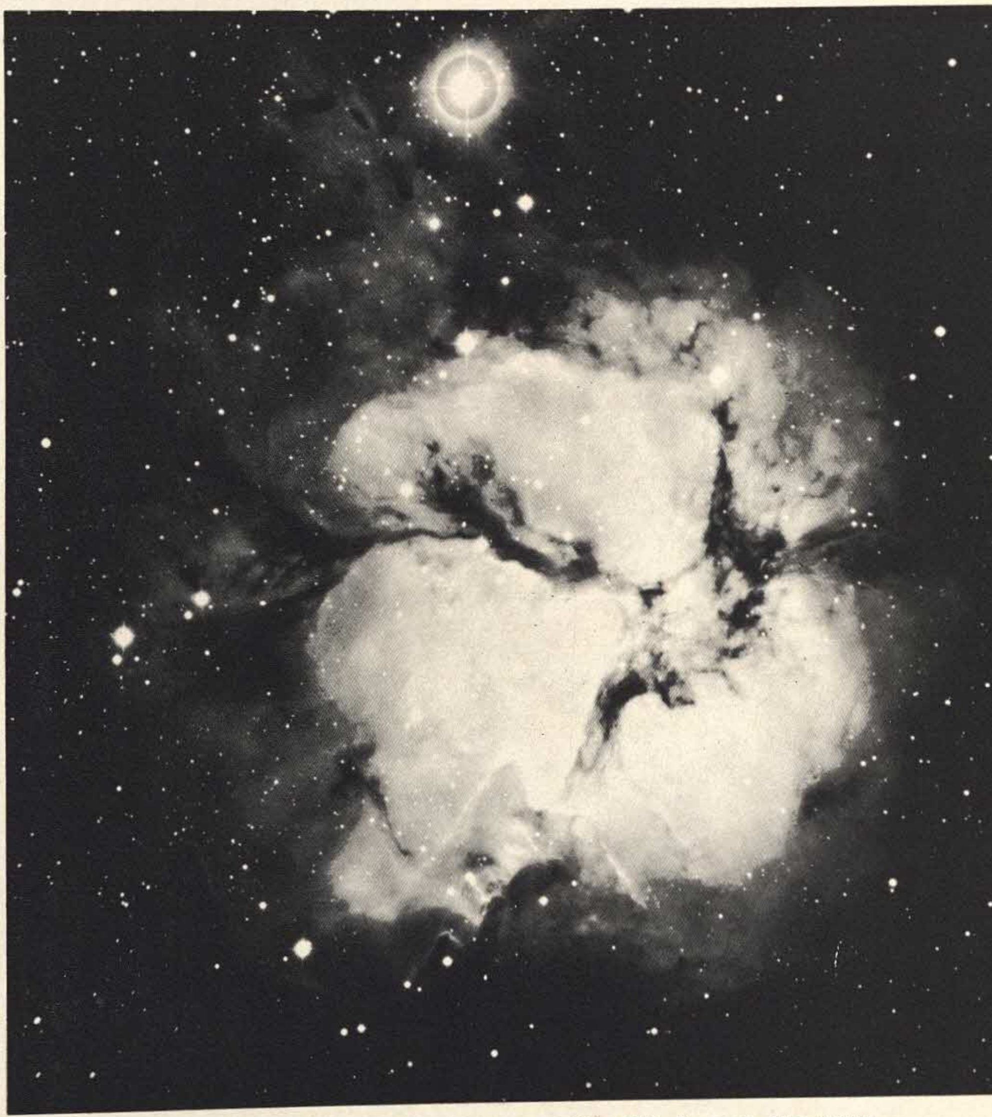

A GASEOUS NEBULA—This nebula is composed of slightly luminous gas dispersed in space and resembling a wispy cloud. This nebula is not composed of stars, although some are visible within its mass. Also visible is microscopically fine dust dispersed in space and obscuring underlying stars.

OBSERVING CLUSTERS AND NEBULAS

Since globular clusters and nebulas emit very little light, they must be observed through a telescope that has low magnification and hence a bright image. A telescope with high magnification (high power) would yield a larger image, but in general such an image is too faint for effective viewing of nebulous objects. Binoculars and telescopes with short focal lengths are particularly suited because these instruments generally have relatively low magnification.

Nebulas and globular clusters may cover a considerable area in space. Their diameter as seen from Earth is frequently equal to many times that of the largest planets. Fortunately, their size makes magnification of more than 20 to 50 X unnecessary.

Nebulas and globular clusters are best observed when the sky is totally dark and relatively free of atmospheric haze, since the weak light of nebulas and globular clusters is diffused by a hazy atmosphere until it is no longer visible. Planets may be observed successfully even in a rather dull or hazy sky, as long as no atmospheric disturbance interferes. A slight wind does not influence the intensity or visibility of nebulas, but does interfere with observation of globular clusters; the images of the stars within them appear as indistinct blurs rather than as sharp points of light. Observers of globular clusters and nebulas must avoid looking at the moon, as the brilliance of even a thin crescent blinds the eyes to the faint nebular light.

PHOTOGRAPHY

Photography is widely used in astronomical research because it provides objective evidence, and has been put to good use in the study of weakly luminous nebulas and globular clusters. Although these objects appear faint on direct observation, long photographic exposure allows their images to be clearly fixed on film. This can be seen in the accompanying illustrations.

Looking at nebulas and faint clusters of stars through a telescope points up an interesting fact about the sensitivity of the human eye. The outer portions of the retina are more sensitive to weak light than the center. To make the image of the nebula fall on this outer portion of the retina it is necessary to look to one side of the object being observed. This rather unnatural method of observation is difficult at first because an observer always tends to look directly at the object of interest; however, the technique of "averted vision," as it is known, is easily learned and the observer is rewarded with a much brighter and more detailed view of the nebula.

A NEW STAR CAMERA

An optical system that revolutionized nebular photography was invented by Bernhard Schmidt in about 1930 at the Hamburg Observatory in Bergedorf, Germany. He placed a thin, weakly curved, aspherical lens at the center of curvature of a spherical mirror and achieved in this simple way a system that has high speed, large field, and almost color-free images. The rapid introduction of the Schmidt telescope into astronomy is due largely to Schmidt's colleague, Walter Baade, who realized its importance when he went in 1931 to the Mount Wilson Observatory in California. Plans were being made there for a 200-in. reflector, and it was decided to build an 18-in. Schmidt camera as a pilot model survey instrument. Its success was responsible for the design and construction after World War II of the 48-in. Schmidt telescope on Mount Palomar. The new

DIFFERENT NEBULAR OBJECTS—These photographs show the four principal types of celestial objects with a nebular appearance. Each has a completely different physical structure. The extragalactic nebula shown in Illustration 2a consists of a group of approximately ten billion stars interspersed with dust clouds. Extragalactic nebulas are so large that light, which travels at a velocity of 300,000 km/sec (about 186,000 mi/sec), takes about 100,000 years to cross one of them. Millions of extragalactic nebulas exist, although not all have been observed. In the Southern Hemisphere, only one, the so-called Large Magellanic Cloud, is visible to the unaided eye; three or four can be seen with binoculars, and a few hundred more are visible in a clear sky, through a 15-cm (6-in.) telescope.

The most commonly observed extragalactic nebulas are estimated to be at least a half

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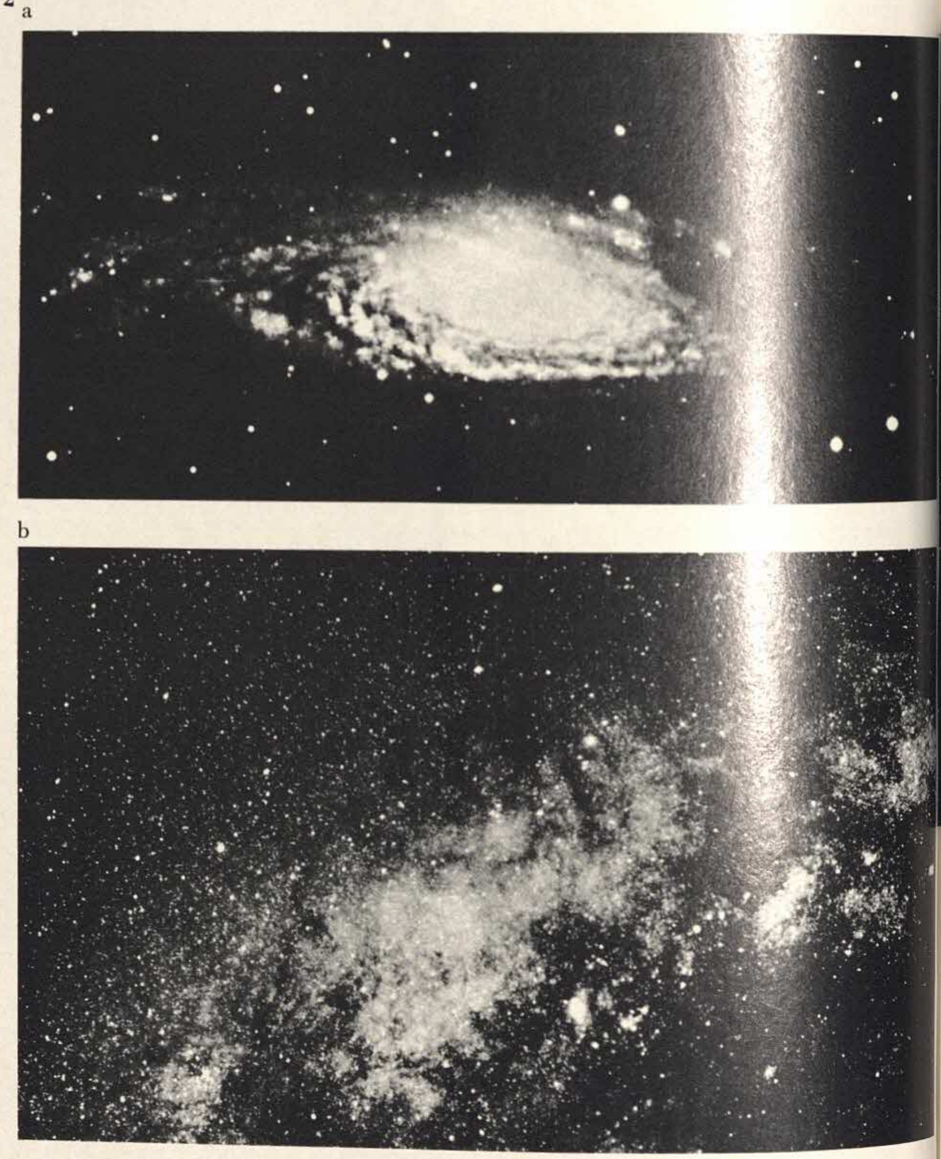

million light-years distant from Earth. Those nebulas that can be photographed only through the most powerful telescopes are many billion light-years away.

The Milky Way is composed of star clouds such as that shown in Illustration 2b. The photograph shows that star clouds are made up of numerous stars that appear to be very close together. Actually, their distance from each other is about the same as the distance between the sun and the nearest stars. The stars in a star cloud are seen in such abundance because they cover the sky for great distances. Star clouds can easily be resolved into stars, even through binoculars.

To the eye a globular cluster (Illustration 2c) resembles a small luminous spot not unlike a star with blurred outlines. It is composed of hundreds of thousands of stars distributed within a spherical or slightly ellipsoidal area. The most familiar globular clusters are situated away from the plane of the Milky Way. Clusters in the borders of other galactic systems are invisible to an amateur's telescope, and are barely visible to the most powerful instruments.

An open cluster (Illustration 2d) is composed of a group of stars inside a star cloud. These stars are closer together than most other stars in the Milky Way or in other galaxies.

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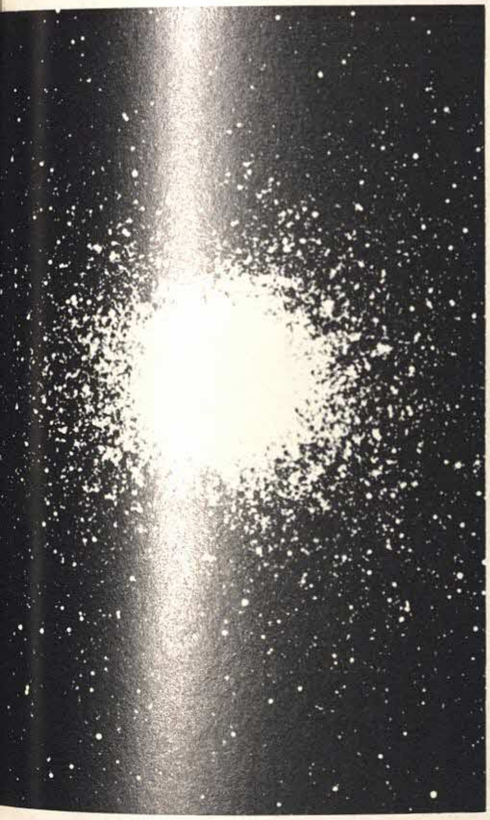

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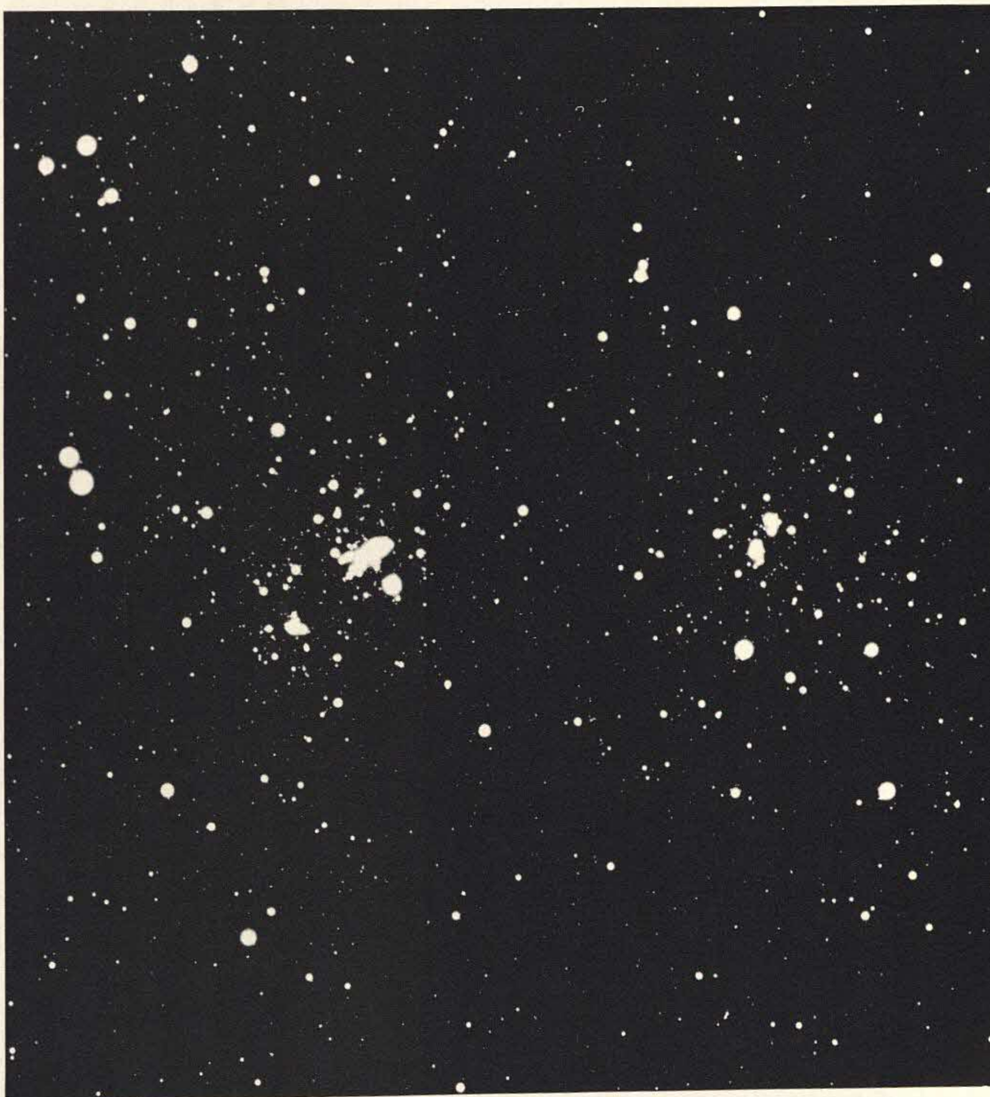

telescope's performance in 1948 and 1949 so far exceeded all previous wide-field, faint-limit photographs that its first program was to survey all the sky observable from the Northern Hemisphere. The 48-in. Schmidt telescope was used subsequently to obtain the 879 plate-pairs—one exposure in blue light and one in red—that make up an atlas covering three-quarters of the sky.

THE GREAT REFLECTORS

G. E. Hale, who had put a 100-in. reflector into operation on Mount Wilson in 1919 with gratifying results, initiated the building there of a 200-in. reflector in 1928. Edwin Hubble took the first nebular photograph with the 200-in. reflector on January 26, 1949. It was by then known as the Hale telescope.

Also used extensively for nebular research are the 120-in. reflector at the Lick Observatory on Mount Hamilton in California and the 84-in. reflector at the Kitt Peak National Observatory in Arizona. Basically, the Lick 120-in. telescope has a design similar to that of the 200-in. Hale telescope. The 84-in. telescope uses a design known as the Ritchey-Chrétien, developed in the 1920s but not used in an earlier instrument than the Kitt Peak telescope. This design, named for G. W. Ritchey and H. Chrétien, gives a field both larger and flatter than an ordinary reflector provides. The scale is similar to that of the Hale instrument.

OBSERVING THE PLANETS | a guide for planet watchers

The night sky is not only a treasury of spectacular beauty and surprising richness; it is also one of the most accessible of natural phenomena, visible without the expense of travel. To observe distant stars and planets, a suitable magnifying device is necessary, but this need not be costly or cumbersome—a pair of binoculars will suffice to observe the stars and planets, and a small telescope offers a lifetime of observation of the ever-changing celestial scene. Some planets, for example, change in appearance from one night to another.

A reflecting telescope with a 6-inch mirror will reveal more than 100,000 stars, hundreds of double and multiple star systems, and galaxies beyond the Milky Way. With such an instrument, the moon appears to be only about 1,000 miles away, and its surface features can be clearly distinguished.

The night sky is vast, however, and its landmarks must be learned. This task can be pursued in stages. The first stage involves learning the constellations, the patterns in which the brightest stars

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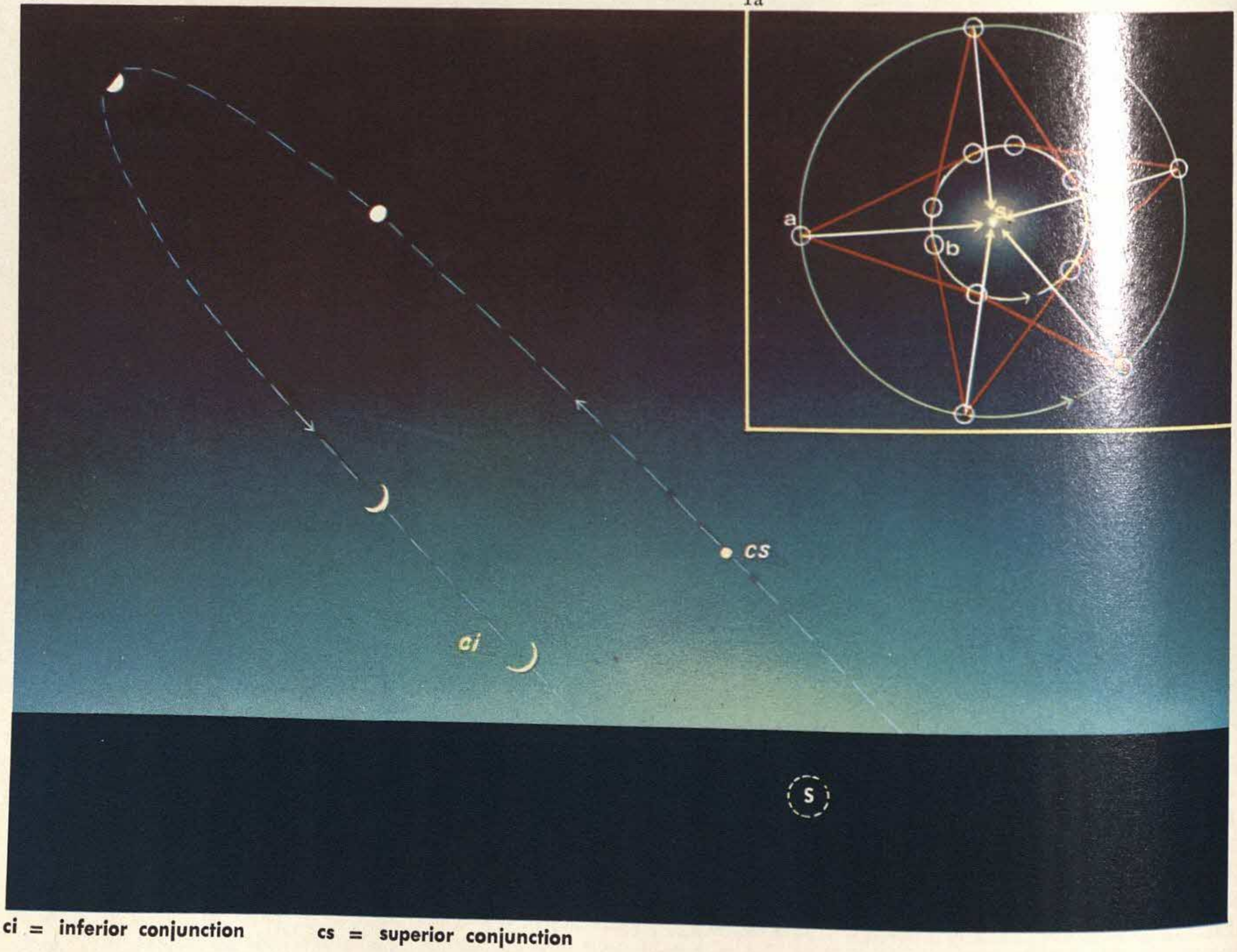
THE INFERIOR PLANETS—The two planets whose orbits are closer to the sun than the Earth's orbit are Mercury and Venus. Illustration 1a shows why, when viewed from the Earth, these planets are never seen far from the sun. No matter where the Earth may be in its orbit **a,** and no matter where the planet may be in its orbit **b,** the angle from the planet to Earth to the sun is an acute angle. If the planet is not visible before dark, the observation should begin as soon as possible after sunset, when the planet will be just above the horizon.

Illustration 1b shows the path of the planet Mercury. The dotted circle **S** indicates the position of the sun beneath the horizon: **cs** represents the superior conjunction of the planet, when the sun is between the Earth and the planet; and **ci** represents the inferior conjunction, when the planet is between the Earth and the sun. If the planet is observed too late after sunset, it will have descended so close to the horizon that its image will be distorted; if it is observed too soon, the twilight may make the planet almost invisible. Venus may be seen long after sunset, whereas Mercury may be seen only for short periods of time.

1b

1a



ci = inferior conjunction **cs = superior conjunction**

appear. Because the Earth rotates, the location of the constellations varies seasonally and also during each night, and these locations must be studied if specific celestial bodies are to be located according to their charted positions within the constellations. To interpret maps of the sky, only the unaided eye or a pair of low-powered binoculars are needed at first. Later, more detailed charts will make it possible to find, among the brightest stars whose positions have been memorized, the more obscure planets, stars, nebulas, and star clusters—celestial bodies with particular visual characteristics.

PLANETARY OBSERVATIONS

An extensive background in astronomy is helpful for a thoroughly profitable observation of the sky, and everything available should be read about the bodies themselves. This is particularly useful in observing the planets, some of which are not easy to identify and to·distinguish from stars. Even though they are spheres, relatively near the Earth, and in size comparable to the Earth (from about half to about 11 times as large), they appear to the eye as luminous points unless they are seen through a telescope or powerful binoculars.

Only seven of the planets are likely to be seen with binoculars. These are sometimes distinguished as the inferior planets—Mercury and Venus, whose orbits are nearer to the sun than the Earth's orbit—and the superior planets, Mars, Jupiter, Saturn, Uranus, and Neptune, with more distant orbits. (Pluto is so dim and distant that a 20-inch telescope is required to see it, and even then it is not easily distinguished from the many faint stars in the telescopic field.) The superior planets can be seen with the naked eye, but binoculars are needed for Uranus and Neptune. It is also necessary to have charts of the regions in which Uranus and Neptune are to be found at a specific time, so that the stars around them can be used as a guide for location. Inasmuch as all the planets change their positions constantly, the charts are limited in their use, and the proper chart must be found, year by year. These charts can usually be found in popular astronomy periodicals.

Although charts are useful in locating the five visible planets, they can be identified by their own distinctive characteristics. For one thing, unless weather conditions are particularly poor, planetary light is fairly constant and does not twinkle like starlight. The brighter planets are sometimes even mistaken for low-flying objects in the Earth's atmosphere, and in one case a planet was confused with a reconnaissance balloon during a war and fired on. In any case, some planets shine more brightly than most stars. Each planet exhibits a distinctive color if the atmosphere is extremely clear. Venus and Mercury shine with a silver-white light; Mars is reddish; Jupiter is ivory-white; and Saturn has a greenish tinge.

OBSERVATIONAL FEATURES

Mercury, the smallest of the planets, often is not noticed, primarily because it is very near the sun most of the time; it is never more than 28° away from the sun.

The other inferior planet, Venus, is by far the brightest planet in the solar system; it is so bright in fact that it is easily visible during the daytime when it is far enough away from the sun.

Through a telescope, both Mercury and Venus exhibit phases that are similar to the phases of the moon. Both planets are best observed just after sunset or just before sunrise; of the two, Venus is much more readily observed, and it may be seen for a longer period.

The surface details of Venus may not be observed even with a telescope, because this planet is surrounded by a very dense atmosphere. On the other hand, the surface markings of Mars can be observed fairly well, because this planet has a very thin atmosphere. Seasonal changes can even be noted with a low-powered telescope. With the advent of summer, the polar caps shrink, and the brownish-colored regions acquire a greenish-gray appearance. Mars is best observed when it is in opposition—that is, when it is in a direction opposite that of the sun.

Jupiter, the largest and most massive of the planets in the solar system, offers several interesting features for observation. One of these features is its banded appearance. The irregular bands or belts that run more or less parallel to the planet's equator vary in number, breadth, and position from one year to the next.

Another interesting feature is the well-known red spot, which may be observed with the aid of a small telescope. Although this spot is basically elliptical, it varies somewhat in size and shape; in the past, its color has varied from an intense red to a very faint gray.

The satellites of Jupiter also provide interesting subjects for study. Four of Jupiter's twelve satellites are visible with binoculars. These four satellites, which were the first bodies in the solar system to be discovered with a telescope, probably could be seen with the unaided eye if it were not for the glare of the planet itself. (Next to Venus, it ordinarily is the brightest of all the planets.) Observation of the remaining eight satellites requires the use of very powerful instruments.

To the naked eye Saturn, at opposition, always appears as a very bright star—brighter than the first magnitude. This planet, of course, is noted for its unique system of rings, which may be observed with a relatively low-powered telescope.

Both Uranus and Neptune can be observed with binoculars; when viewing conditions are very good, Uranus may be seen with the unaided eye. Because of their great distance, neither planet appears as more than a very small disk, even through a high-powered telescope.

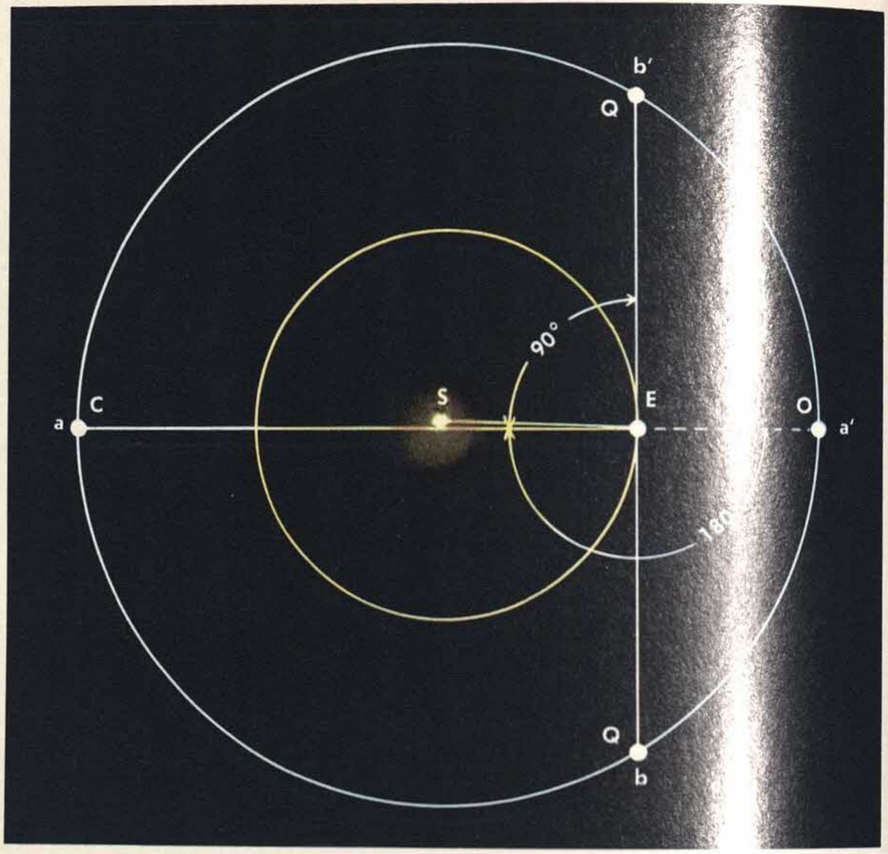
THE FIRST OBSERVATION

When seeking a planet for the first time, it is useful to use a chart in which the position of the planet among the stars is indicated at specific times. Once the planet is located in this way, it can easily be relocated, even after a long period of time and in a different part of the sky. Its motion can be followed, night after night, and the quality of its light will be remembered.

Another criterion that locates a planet after a long time is its observed position compared with its position a year earlier. Each year a superior planet, for example, regresses from its position among the stars at opposition; that is, it moves along the ecliptic in a direction opposite to that of the sun. In the case of Jupiter, this regression is about one twelfth of the zodiac because the revolution of that planet around the sun takes 12 years.

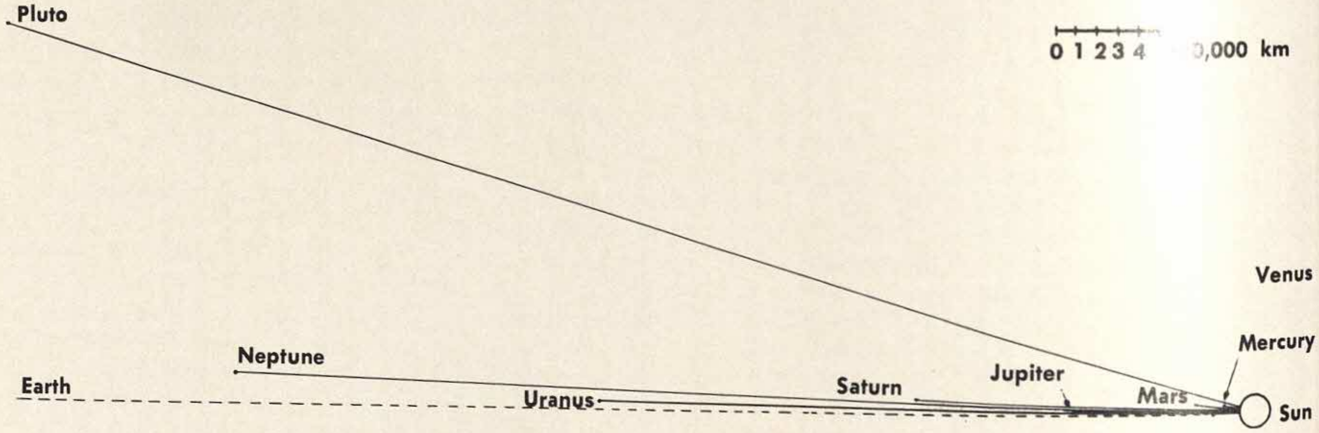
2

a



THE SUPERIOR PLANETS — These are the planets whose orbits are farther from the sun than the Earth's orbit. Illustration 2a shows that a superior planet may be at any angular distance from the sun **S.** Along the outer circle, representing the orbit of the superior planet, at **a** the planet is in the same direction from the Earth **E** as the sun; this position **C** is called conjunction with the sun. At **b** or **b¹** the planet is at an angle of 90° from the sun, to the east **b** or the west **b¹**; this position **Q** is called quadrature. At **a¹**, the planet is in a direction opposite to that of the sun, and is said to be in opposition **O.** This is the best position for the observation of a superior planet; at that time its distance from the Earth—the difference between its distance from the sun and the Earth's distance from the sun—is at a minimum. A planet reaches its maximum height above the southern horizon at midnight.

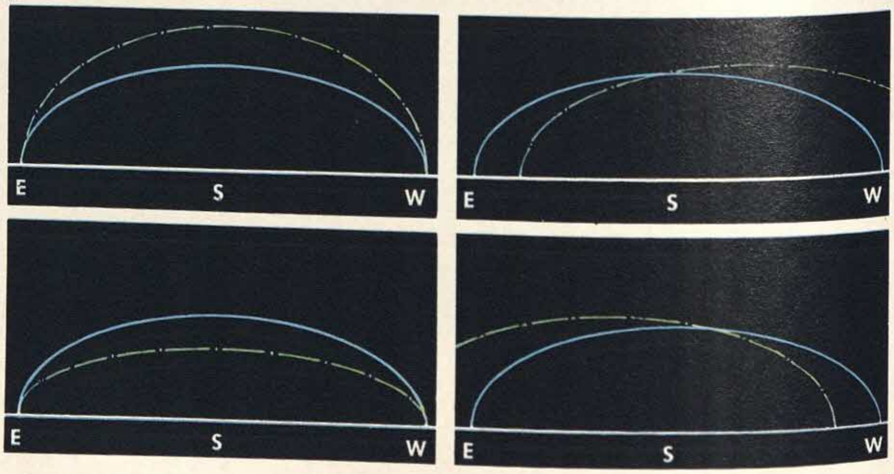
b



The orbits of all the planets that are visible lie in virtually the same plane, separated very little from the plane of the Earth's orbit. Illustration 2b shows how the solar system would appear in profile if all the orbits were inclined on about the same axis at the same time. Because of these inclinations, the planets move away from the ecliptic to some degree, according to the inclination of the orbit and the position of the planet in the orbit. The constellations along the ecliptic are called the constellations of the zodiac, and the planets always appear among these constellations.

The height of the ecliptic (dotted line) above the southern horizon varies, because the inclination of the ecliptic to the celestial equator (solid line) depends on the season and the hour of the night. Illustration 2c shows the seasonal variations.

c

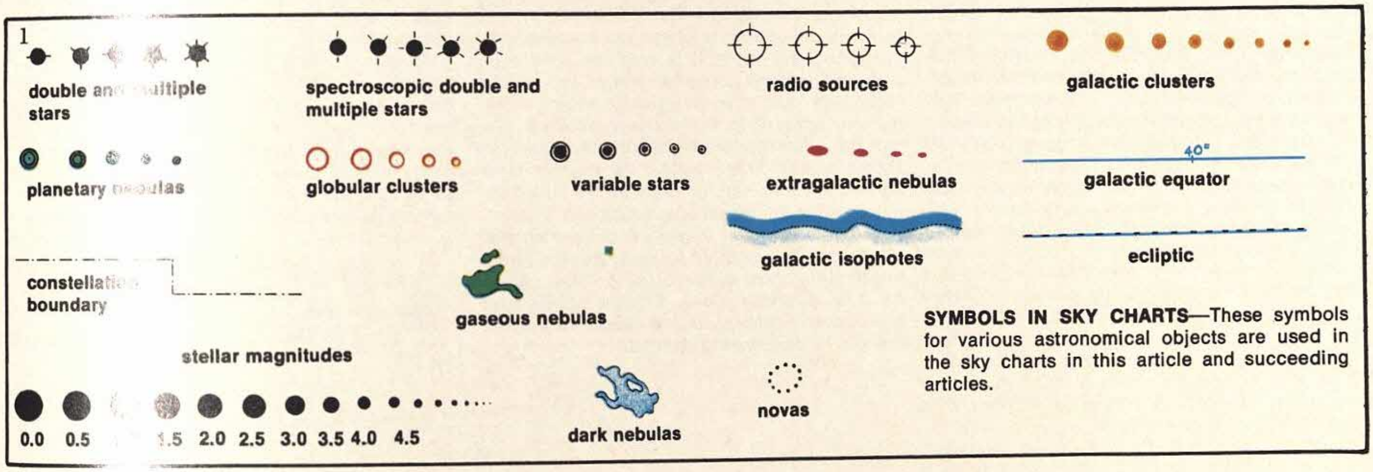


THE SKY IN JANUARY | Camelopardalis, Auriga, Orion, and Lepus

Certain stars and constellations may be seen in the winter sky just after sunset. In the course of 12 hours, the sky makes half a turn, changing the positions of the stars completely. Therefore, in a 12-hour period, an observer can view all the constellations visible at middle latitudes. Usually, however, observations are made during a few hours only—say, between nine and eleven o'clock in the evening. For this reason, this series of monthly star charts shows the sky as it appears during these common viewing hours. The charts show the disposition of the constellations with respect to the horizon and the four cardinal points of the compass. Only the positions of the main stars are shown; small details are not included. The legend in Illustration 1 serves as the key to all the charts in this series.

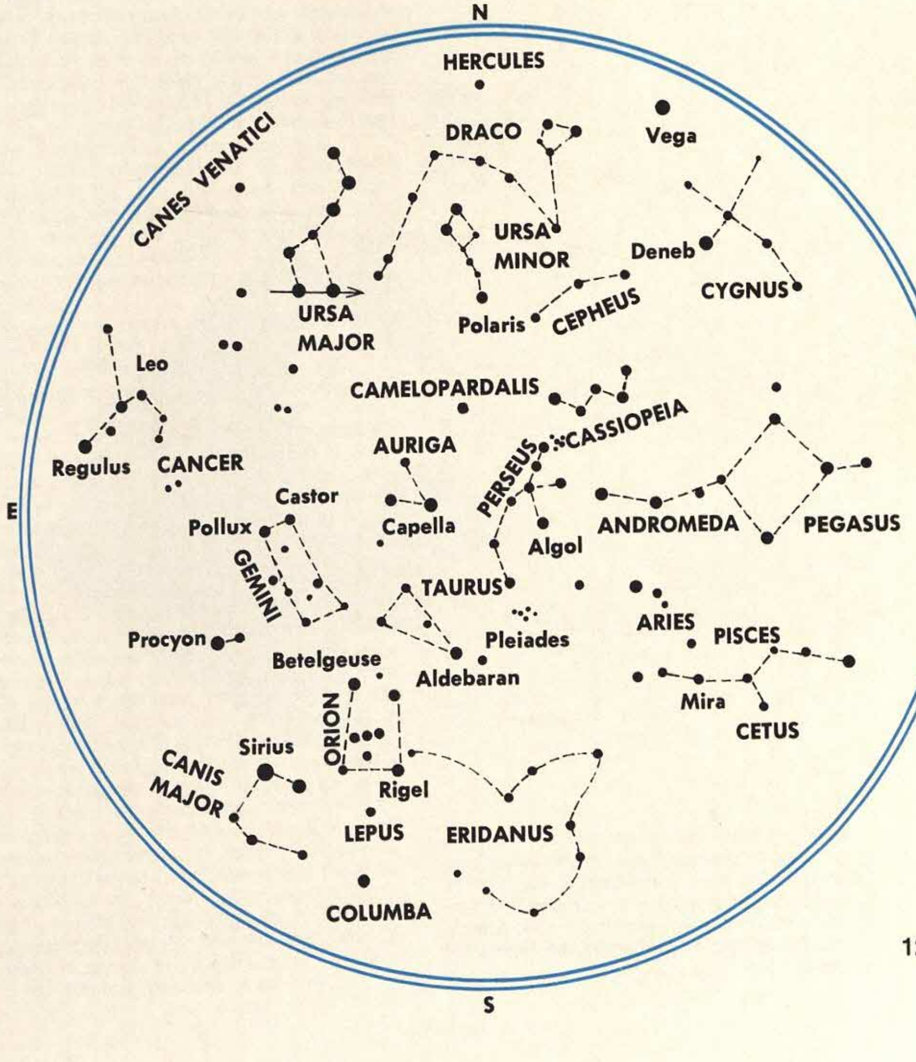
A chart showing the positions of the stars during a certain month may be used to locate them during other months; the observer must count two hours earlier for each succeeding month or two hours later for each preceding month. For example, the constellations have certain positions

1



SYMBOLS IN SKY CHARTS—These symbols for various astronomical objects are used in the sky charts in this article and succeeding articles.

2



THE JANUARY SKY — This chart shows the approximate positions of the constellations visible during January.

The ever-present Ursa Major (the Great Bear) is in the eastern sector of the sky—still low on the horizon, although it rises higher in the course of the night. To the east Leo (the Lion) is rising; Regulus is already above the horizon, and its appearance presages the coming warmth of spring. Relatively few stars are visible between Ursa Major and Regulus. High on the horizon in the east is the constellation Gemini (the Twins, Castor and Pollux).

On the southeastern horizon, the area is only thinly populated with stars, but at a greater height toward the south are many brilliant stars. Most splendid of all is Sirius, in the constellation Canis Major (the Great Dog); to the southeast is the constellation Canis Minor (the Little Dog), where Procyon shines brightly. Finally, on the meridian, are the stars of the constellations Lepus (the Hare), Orion (the Hunter), and Auriga (the Charioteer).

The western sky boasts many beautiful constellations, many of which brighten the sky during the preceding months. Low on the horizon from north to south are Cygnus (the Swan), Pegasus, Pisces (the Fishes), and Cetus (the Whale). Some of them lie so low on the horizon that they are only partly visible, but they can still be observed because the sun sets early in winter; just after sunset, they are located much nearer the meridian.

Auriga, Andromeda, and Cepheus are still quite high on the horizon, and may be observed well into the night. Perseus is also quite high, and Taurus (the Bull) is quite near the meridian.

Constellations that will be described in more detail are Camelopardalis (the Giraffe), Auriga, Lepus, and Orion. In January, Camelopardalis is found between the zenith and the pole. Its stars are so faint that they are almost invisible to the eye, but a few can be seen.

at 10:00 P.M. in January; they have the same positions at 8:00 P.M. in February and at 12:00 midnight in December.

The spectacle offered by the calm, cold night sky in January more than compensates for the frosty weather, insofar as astronomers are concerned. Ordinarily the clearest nights of the year occur during the first month.

CAMELOPARDALIS—The constellation of the leopard-camel (the meaning of the Latin name used in some star atlases for the Giraffe) has few bright stars, but it is quite extensive both in right ascension and in declination. It reaches almost to the north pole and extends southward to 50° declination; in right ascension, it extends from about 3 hours to about 14 hours. About 80 double stars may be seen in this constellation, but they are not remarkable for their luminosity or any special characteristics of their components. The brightest does not reach the 4th magnitude, and among the brightest are many extremely weak stars. Many of the stars are too dim to be observed with a small telescope. Some extremely dim extragalactic nebulas and a planetary nebula are among the other celestial objects worth noting in this area of the sky.

AURIGA—One of the most interesting constellations in the winter sky, Auriga extends approximately from north declination 28° to 56°; in right ascension, it extends for about 3 hours. Where it is highest in declination, it is circumpolar—that is, it is visible above the horizon the year around. Its brightest star, Capella (α), skims the summer horizon, never setting below it, although it is difficult to observe with the naked eye when it is very low. The constellation extends along the winter axis of the Milky Way, and it is very rich in celestial objects of interest to the amateur observer. To find the constellation in the sky, the observer should note its four principal stars, which form a pentagon with Nath (β Tauri, on the boundary between the constellations Auriga and Taurus).

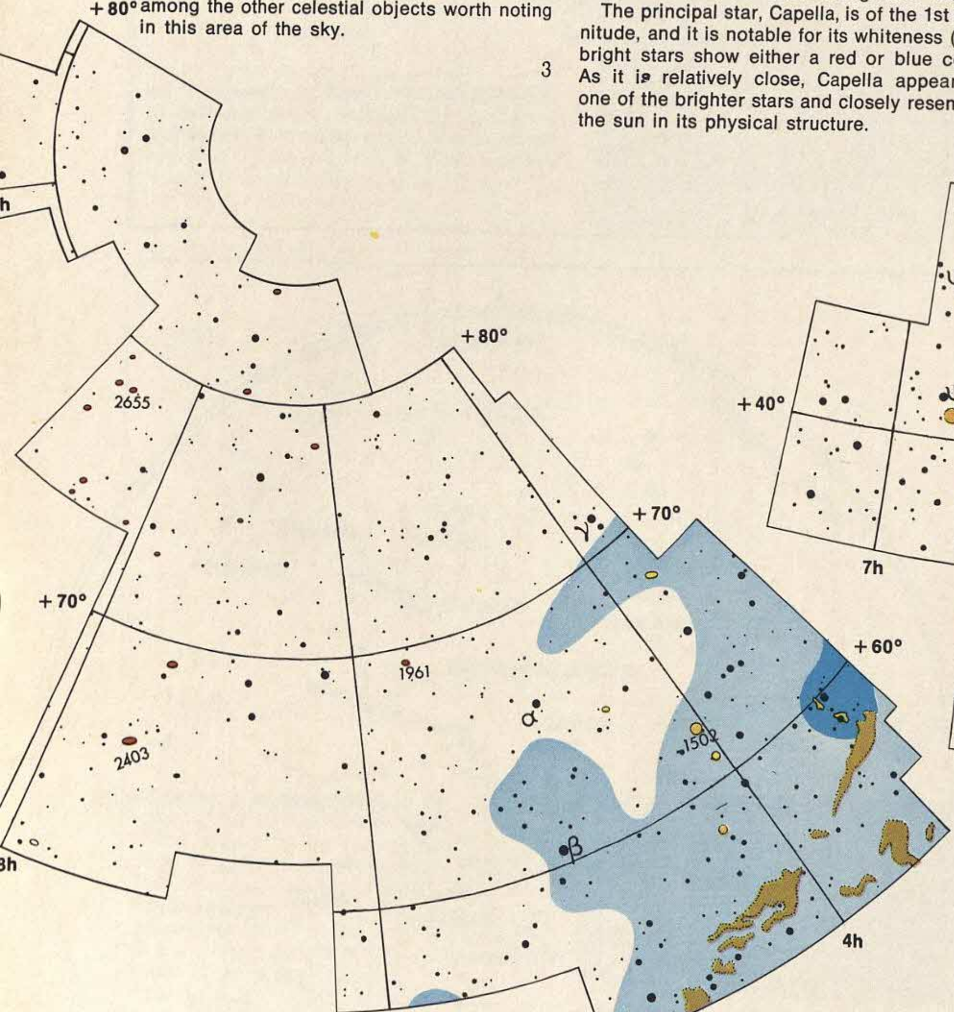
The principal star, Capella, is of the 1st magnitude, and it is notable for its whiteness (most bright stars show either a red or blue color). As it is relatively close, Capella appears as one of the brighter stars and closely resembles the sun in its physical structure.

The constellation Auriga is rich in double stars, which can be observed with a 15- to 25-cm (about 6- to 10-in.) telescope; however, most of them are of low luminosity. Only Omega (ω) is of significance; it is composed of a star of magnitude 4 and another of magnitude 7.9. The distance separating them is 6.5″ (seconds of arc), a distance that even a small telescope can resolve.

Epsilon (ε), near Capella, is also worth observing, although a stronger telescope may be required. This is a double star of the spectroscopic type. The primary star is considerably larger and dimmer than the secondary star, which is quite small and bright. Because of its size, the primary star is referred to as a giant. In the course of its revolution around the primary star, the secondary star becomes hidden; the giant, because of its size, is surrounded by an extensive semiopaque atmosphere that gradually conceals the light of the secondary star.

A wonder of this constellation is the number of galactic clusters it contains—eleven in all. Five are found in the triangle formed by Iota (ι), Theta (θ), and β Tauri. On a clear night, a small telescope reveals the innumerable stars in the center of each cluster. An extremely bright cluster may be seen slightly to the west of β Aurigae, on the border with Perseus; another luminous cluster is on the border with the constellation Lynx. The others are somewhat dimmer and can be seen only through high-powered telescopes. In the brightest clusters, hundreds of stars can be counted; with a 30-cm (about 12-in.) telescope, as many as 500 stars may be seen in the clusters. The entire constellation is covered by a light veil of hydrogen gas and by dust.

3



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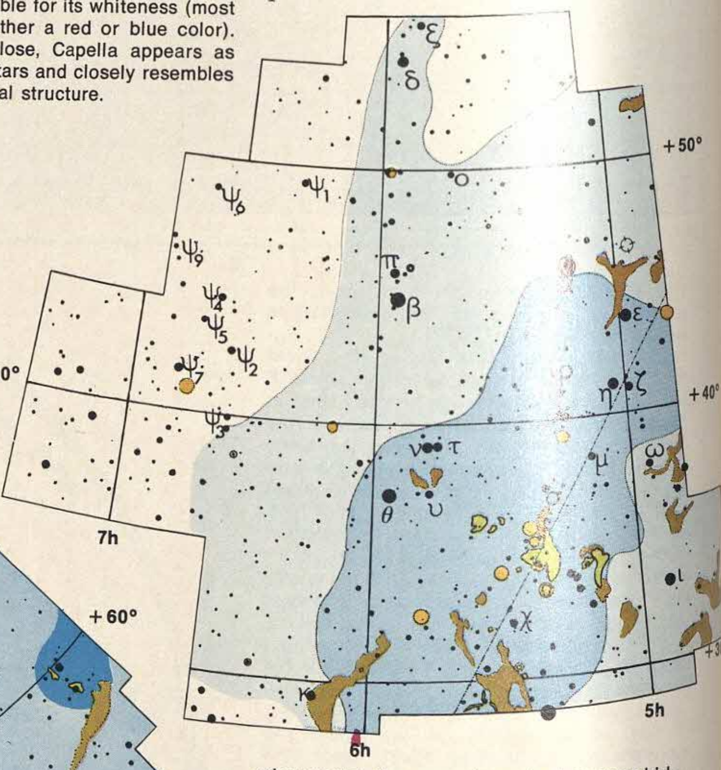
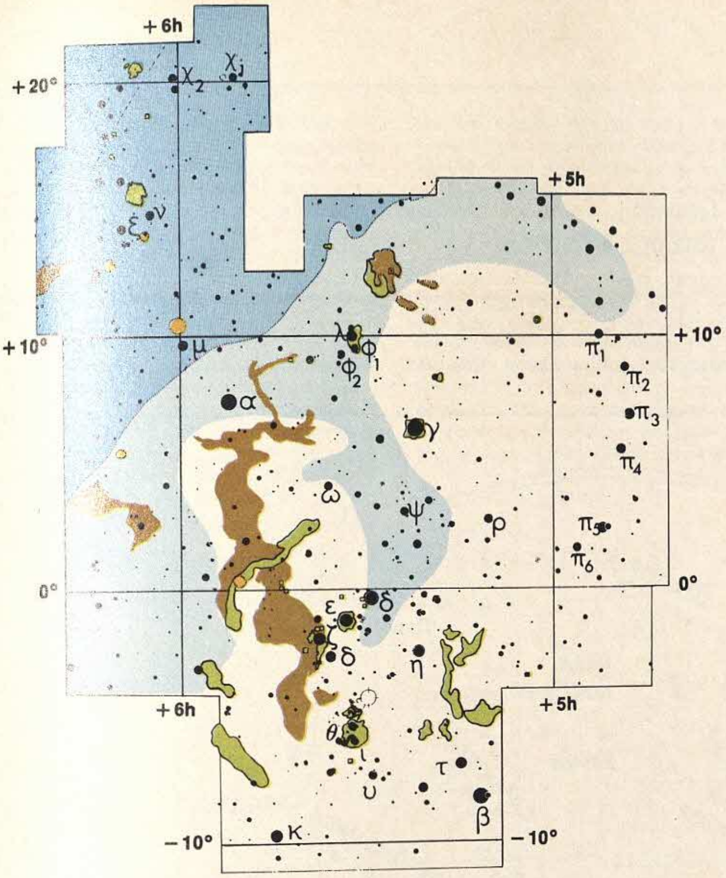


Letters of the Greek alphabet are used on star charts to designate the relative brightness of stars within each constellation. Usually, the brightest star is labeled α, the second brightest β, the third brightest γ, and so on. One notable exception is Ursa Major, where the letters are assigned geometrically.

5



ORION—The design formed by the stars of Orion is as easily identifiable as that formed by the familiar stars of Ursa Major; it is a rectangle formed by the principal stars, with three stars in the center aligned at approximately 45° to the median of the rectangle.

Other objects, notable for their physical characteristics and the ease with which they can be observed through a telescope, are scattered throughout the constellation.

Atlases usually refer to the parts of this constellation by their mythological names. Orion was the figure of a mythological hunter, who was drawn so that the stars α and γ formed his shoulders; β and κ, his knees; δ, ϵ, and ζ, his belt; and θ, the sword hanging from his belt.

Both α and β Orionis are interesting stars. The former is reddish and the latter is bluish-white; on a clear night the contrast between them shows how intense the coloration of stars is. Ancient charts showed α (or Betelgeuse) as brighter than β (Rigel). Today the situation is reversed; therefore, one of the stars, if not both, must have changed in brightness. Betelgeuse is a relatively cool star of the red-giant type, with a diameter greater than the diameter of the Earth's orbit. It was the first star to have its angular diameter measured by a direct method; the measurement was made in 1920.

Rigel and other bright stars in the constellation are blue supergiants. Although their appearance might suggest that they are among the stars closest to Earth, it is their great brightness that makes them shine like powerful beacons, even at a distance of several hundred light-years.

Orion constellation is rich in double stars; about a hundred of them can be observed with a medium-sized telescope, and some are so easily observed that they should be described individually. The easiest star to find is Rigel (β), now the brightest star in the constellation. Beside the main star of the 1st magnitude is another of the 8th magnitude, at a distance of 9″.

Another double star, η, is composed of stars of the 4th and 5th magnitudes at a distance of 1″. The pair is difficult to see with a telescope of less than 10 to 15 cm (about 4 to 6 in.). On the other hand, η is easily visible even through binoculars; it consists of a star of the 2nd magnitude accompanied at a distance of 53″ to the north by a star of magnitude 6.8.

Two stars of the 5th and 6th magnitudes comprise λ; they are 4.2″ apart. This double star can be distinguished even through a glass with a diameter of 5 to 6 cm (about 2 to 2.5 in.). Even easier to observe is ι, which is composed of stars of magnitudes 3.2 and 7.3, about 11″ apart.

A group that can be observed through small instruments is that of the stars forming Sigma (σ)—four stars of magnitudes 4.1, 10.3, 7.5, and 7, separated by distances greater than 10″ each.

The double star ζ is a difficult challenge for a telescope, because its components, of magnitudes 2 and 5.7, are only 2.3″ apart; a telescope of at least 8 cm (about 3 in.) is required to separate them. Its color is also rather unusual; a nineteenth-century astronomer described it as "olivish with a rubicund cast," but to the unaided eye it appears blue-white.

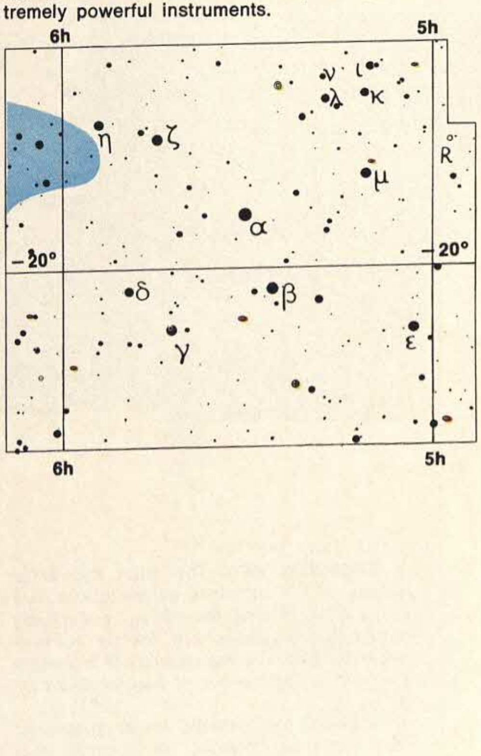
Perhaps the most famous and certainly the most remarkable multiple star in this constellation is θ. Its four principal stars make up a trapezium at the center of the nebula. These stars are of magnitudes 6, 7, 7.5, and 8. Because of their great angular distance, they can be distinguished with the aid of a small telescope. Most spectacular is the gaseous nebula that surrounds the star and extends for more than 1°. On a clear, moonless night, it can be seen clearly with the naked eye; it can be observed even better by looking slightly to the side and around the point where the nebula ought to be. A pair of binoculars or a telescope with low magnification is best for observing this marvel; a telescope with a diameter in excess of 10 cm (about 4 in.) will show the filament structure of the nebula.

6

LEPUS—This constellation is located directly beneath Orion. Because it is in southern latitudes, always low on the horizon of the north temperate zones, its stars are difficult to observe.

The double stars of Lepus do not match Orion's in brightness or in ease of observation. Two objects, however, merit particular attention. One is star R, a bright red star that varies in luminosity between magnitudes 6 and 9. It can be observed with a telescope of low magnification. Its color is quite exceptional, and no other star of such deep color is so bright.

The other interesting object is a globular cluster; through a small telscope, it appears as a symmetrical patch of luminosity with a diameter of about 3′ (minutes of arc). It is a cluster of many tens of thousands of faint stars, and it can be observed only through extremely powerful instruments.

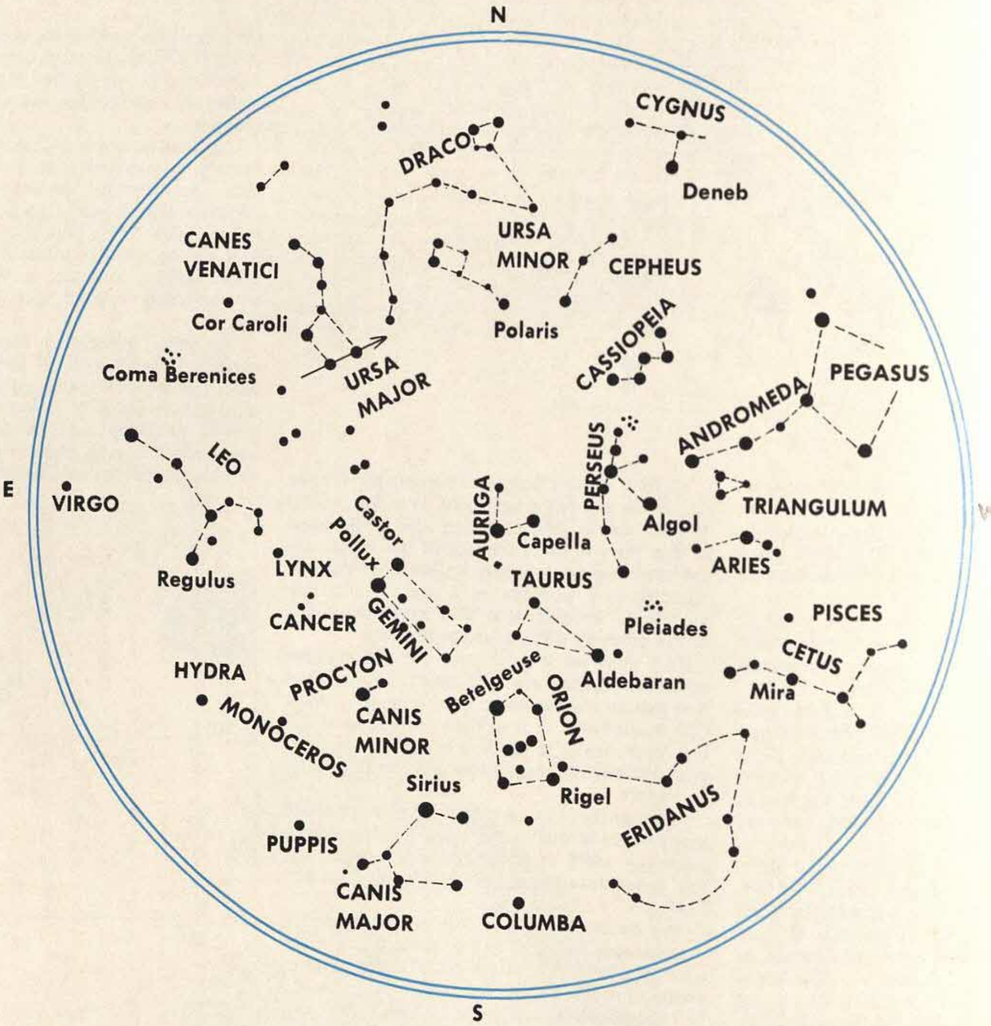


THE SKY IN FEBRUARY

Lynx, Gemini, Canis Minor, Monoceros, Canis Major, and Puppis

During February, the sky is still bright with the winter constellations that constitute the majestic train of Orion, which remains the guide to those celestial bodies that surround it. During this month, the constellations that follow Orion, those to the east, begin to come into prominence.

The February sky is still a winter sky, with many calm, clear nights.



THE FEBRUARY SKY—The chart shows the positions of the principal constellations that may be seen at nine o'clock on a February evening. The positions are merely approximate, because of the impossibility of reproducing an entire hemisphere of constellations on a plane.

After seeing the majestic stellar spectacles of the preceding months, the observer may find the constellations following Orion in the eastern sky somewhat barren. The two Bears are quite high on the horizon. Ursa Major is climbing to the zenith, where it arrives in the spring. In the northeast is the constellation Canes Venatici (the Hunting Dogs). In the east, the great zodiacal constellation Leo (the Lion) is rising; between Leo and the zenith, the sky seems bare of bright stars. To the southeast the constellation Hydra (the Sea Serpent) is rising. Above it is the small zodiacal constellation Cancer (the Crab). On the meridian shine the stars of Puppis (the Stern) and the northernmost part of the Ptolemaic constellation Argo (Jason's Ship), which can be seen in its entirety only in the southern latitudes.

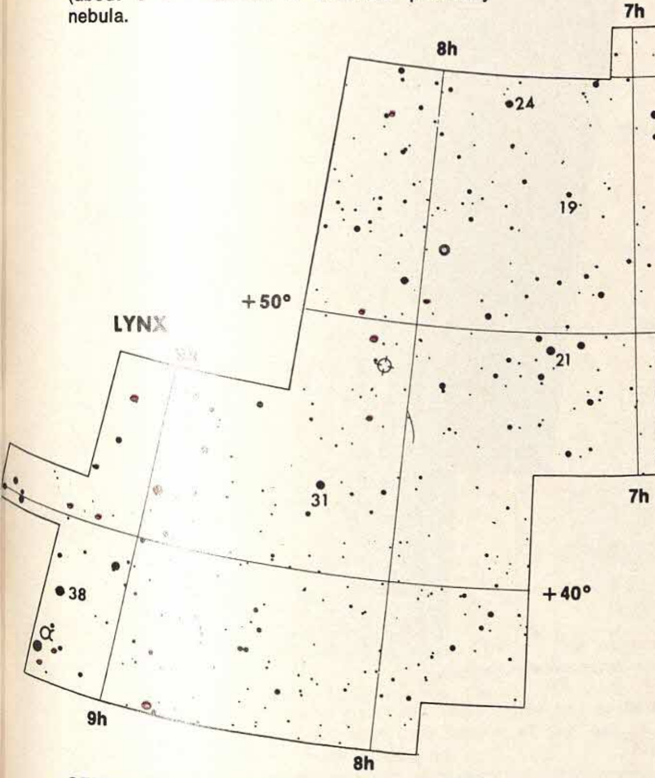
Also near the meridian are the constellations Canis Major and Canis Minor (the Great Dog and the Little Dog), Monoceros (the Unicorn), Gemini (the Twins), and Lynx (the Lynx).

In the west are the beautiful constellations Cassiopeia, Andromeda, and Triangulum (the Triangle) and, near the meridian, Taurus, Orion, and Auriga, as well as Cetus, Aries (the Ram), and Lepus.

Constellations in favorable positions for observation during this month are Lynx, Gemini, Canis Minor, Monoceros, Canis Major, and Puppis.

LYNX—Lynx is a small constellation that lies near the pole; when conditions for observation are favorable, it appears almost at the zenith. It extends for about 30° both in declination and in right ascension. Because it is relatively poor in stars, it is difficult to find even with a telescope. All its stars are dim and quite similar to one another.

Only a few double stars are of interest in this constellation, and all of them are weak and rarely visible. The two most significant are number 19, composed of two stars of magnitudes 5.3 and 6.5 separated by 14.7″, and number 38, composed of two stars of magnitudes 4 and 6.7 separated by only 2.7″. The former is within the range of any small telescope, while the latter can be seen clearly only through a powerful instrument. A telescope of 15 cm (about 6 in.) reveals a beautiful planetary nebula.

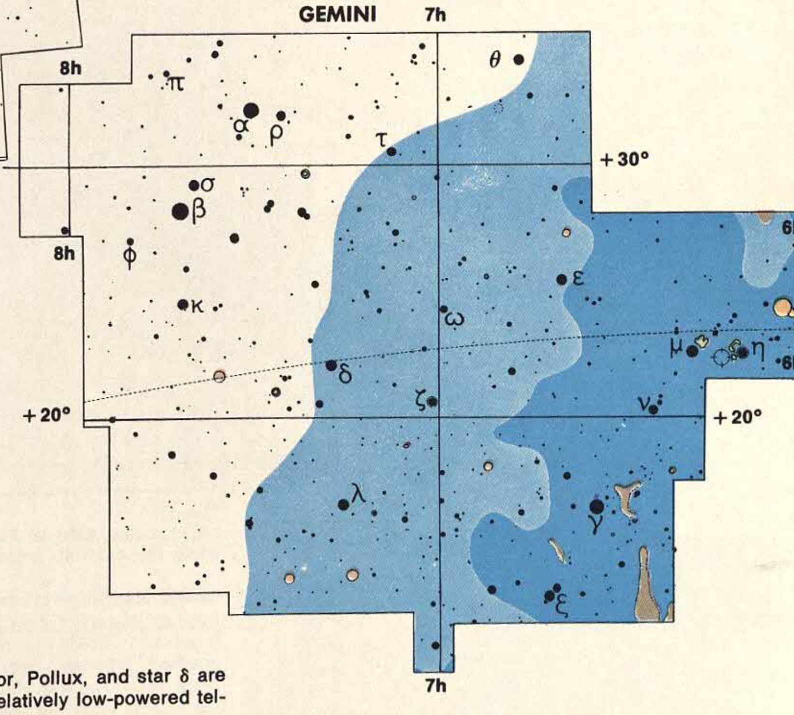


GEMINI—Because of its nearness to the Milky Way, this constellation, covering about as large an area as Lynx, is rich in bright stars and other objects that can be easily observed:

Castor (α) is the most prominent of the double stars in Gemini and is the second star in the constellation in order of brightness. The first is Pollux (β), to the southeast of Castor. A telescope with a 10-cm (about 4-in.) objective and a magnification power of 100 to 125 will show Castor as a double. Its components are of magnitudes 2.7 and 3.7; because of their brilliance, Castor is often called the celestial gem. The distance between the two components is about 5″, depending on when the observation is made, because the rapid revolution of the pair apparently causes them to approach or recede from one another. At any distance the two stars are difficult to separate because both are so bright.

A third star associated with the pair is easy to observe; it is of magnitude 9.5 located 72″ away from the main group. Despite its great distance from the first two stars, it is effectively linked to them in a single system. Furthermore, each of these three observable stars is in itself a double star, but these doubles can be detected only with a spectrograph. Thus, the entire system is really sextuplicate.

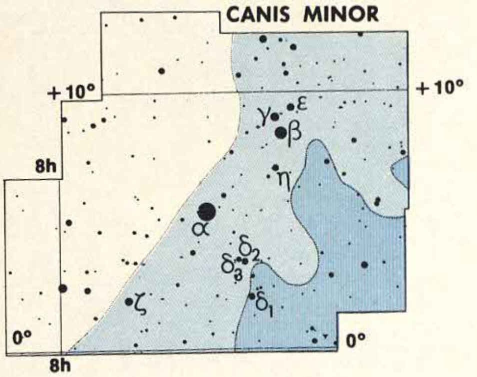
Many other groups of double and multiple stars are indicated on the map; analyzing them through the telescope will show their separations. Gemini also contains many galactic clusters; of these the most notable is that found near stars μ and η. It is a thick cluster quite symmetrical in shape, and it could easily be confused with a globular cluster. The others are considerably dimmer and less populated, but still identifiable. Of the planetary nebulas, only those near Castor, Pollux, and star δ are easily seen through relatively low-powered telescopes.



CANIS MINOR—Ancient stargazers drew Canis Minor and Canis Major as the dogs used by the hunter Orion in the chase. Canis Minor is a small constellation that follows Orion in its movement across the sky. It is located just above the celestial equator at the side of the Milky Way. Despite this proximity, its star cluster and nebulas are beyond the range of small telescopes, with the exception of the principal star, Procyon (α). This star is surrounded by many weaker stars, some of which are doubles; through a telescope pointed toward Procyon, these other stars appear in the field. Procyon's real companion, however, is invisible through a small telescope; it is a star of the 10th magnitude, which makes a revolution around Procyon approximately every 40 years, reaching a maximum distance of 5″. Because of this closeness, the light of the companion is obfuscated by that of the larger star. All the other double stars are too weak to be seen through small instruments.

MONOCEROS—This small constellation between Orion and Canis Major crosses the center of the Milky Way, and is quite rich in interesting celestial objects. It is heavily populated with faint stars, and many gaseous nebulas and dust clouds are found there, along with 16 galactic clusters. Some of the galactic clusters contain easily identifiable stars, but all of them are so faint that they are quite difficult to see with the unaided eye.

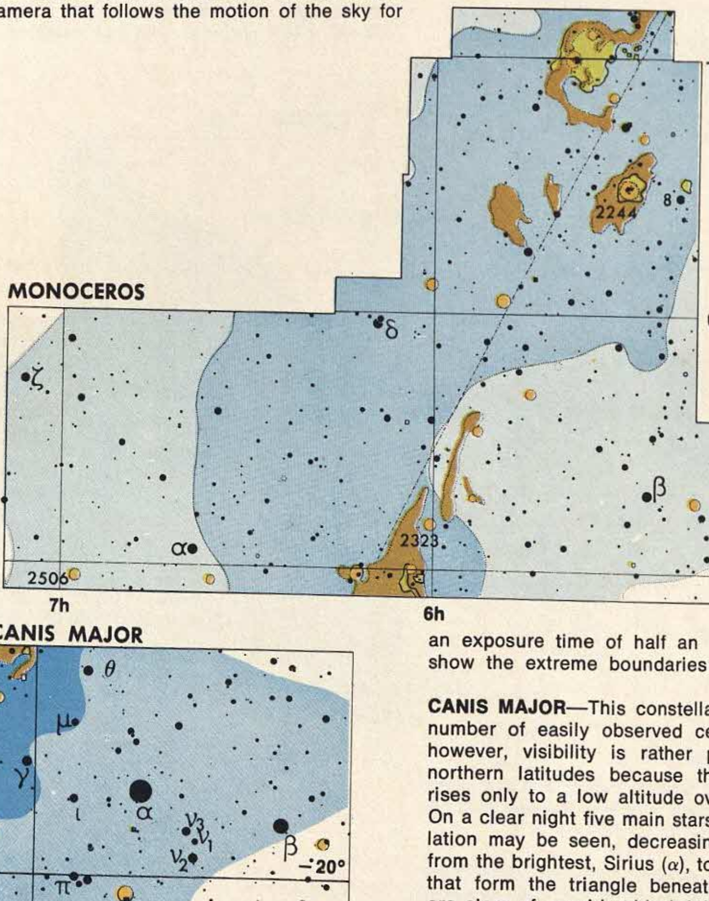
Two of the double stars are especially notable. The star marked 8 is actually a double, with the principal having a magnitude of 4 and the secondary a magnitude of 6.7. Because they are 13.9″ apart, they can be distinguished through even the smallest telescope. They are colored yellow and lilac. The star identified as

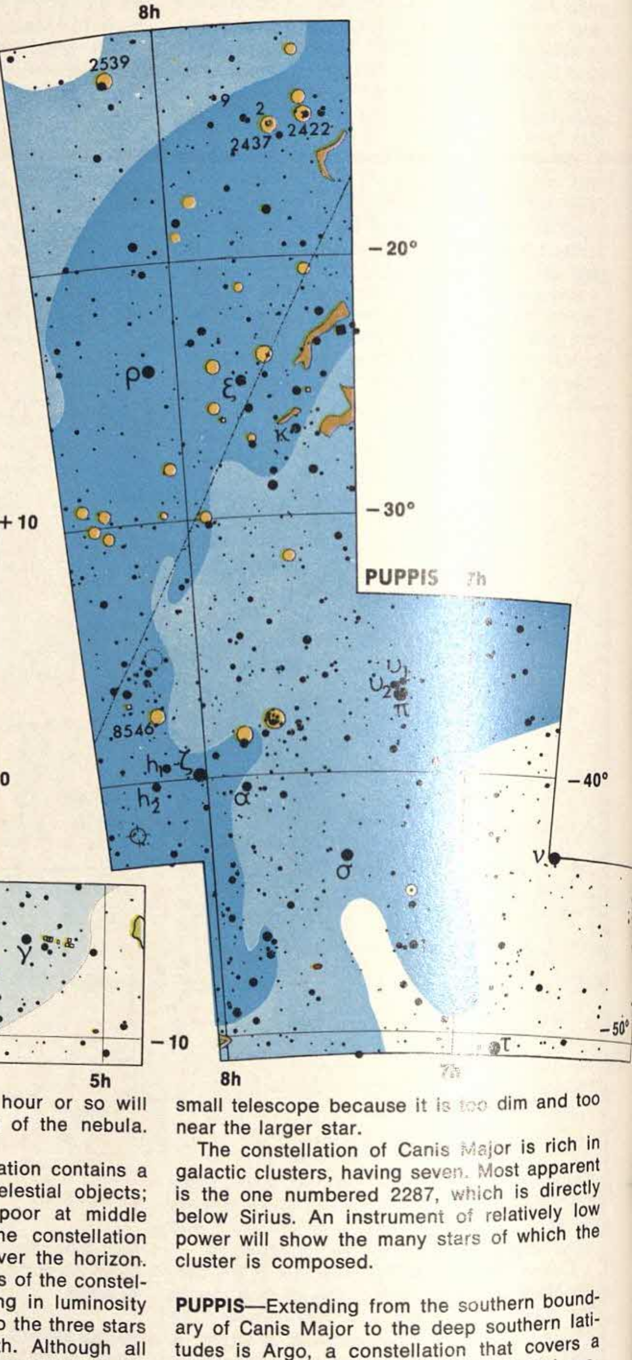


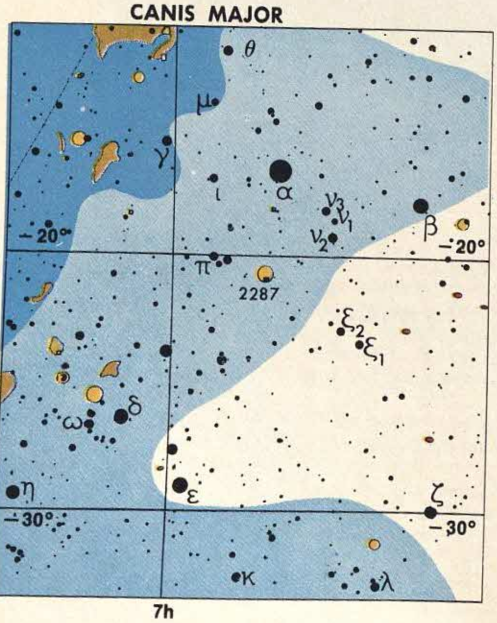
β is a triple star; the secondary and tertiary stars are located 7.2″ and 2.5″ from the main star and have magnitudes of 5.5 and 6 respectively. The primary is of magnitude 5. The group is easily observed, although distinguishing the third star provides a stern test of the resolving power of the telescope.

All the clusters in this constellation are of the galactic type. The one numbered 2244 is the most attractive; it contains a dozen stars of magnitude 6 and many between magnitudes 7 and 9. Other easily observed clusters are those numbered 2323 and 2548; the latter consists of stars of magnitude 9, which do not appear on this chart.

Monoceros also contains extensive nebulas, the most noteworthy of which is found in the upper part of the constellation in alignment with α Orionis and γ Orionis. This nebula can be observed only on an exceptionally clear night with the aid of a powerful telescope of low magnification. A photograph taken with a camera that follows the motion of the sky for an exposure time of half an hour or so will show the extreme boundaries of the nebula.







CANIS MAJOR—This constellation contains a number of easily observed celestial objects; however, visibility is rather poor at middle northern latitudes because the constellation rises only to a low altitude over the horizon. On a clear night five main stars of the constellation may be seen, decreasing in luminosity from the brightest, Sirius (α), to the three stars that form the triangle beneath. Although all are stars of considerable brightness, they appear dim in comparison with Sirius, the brightest star in the entire firmament, northern and southern. Sirius, like some other stars (Betelgeuse and Rigel, for example), has undergone changes over the centuries; many ancient writers described it as reddish, but today it is a brilliant blue-white. Because it is so low on the horizon, Sirius is subject to strong refraction, which breaks up its light and makes it appear polychromatic; this phenomenon can easily be seen with the naked eye.

This star is one of the closest to the sun, about 8.6 light-years away. It, too, is a double star, but its companion cannot be seen with a small telescope because it is too dim and too near the larger star.

The constellation of Canis Major is rich in galactic clusters, having seven. Most apparent is the one numbered 2287, which is directly below Sirius. An instrument of relatively low power will show the many stars of which the cluster is composed.

PUPPIS—Extending from the southern boundary of Canis Major to the deep southern latitudes is Argo, a constellation that covers a vast area. This is subdivided into several sections, of which Puppis is the most northerly. Despite its northernmost position, it is only partially observable at middle northern latitudes, for part of it is always concealed beneath the horizon, and one part never rises to view. Its 24 galactic clusters can rarely be viewed in these latitudes; the only ones clearly visible in a telescope are those numbered 2539, 2437, and 2422. The only easily observable double star is number 2, made up of two stars of magnitudes 6.2 and 7, 16.5″ apart. Number 9 is another interesting star, which can be viewed only with a powerful telescope.

THE SKY IN MARCH | Hydra, Cancer, Sextans, and Leo Minor

"In like a lion, out like a lamb" reflects this month's intermediary role in the skies as well as on Earth. The spring constellations are already visible, although not all of them are on the meridian, and many of the winter constellations are still present. Orion, Canis Major, Canis Minor,

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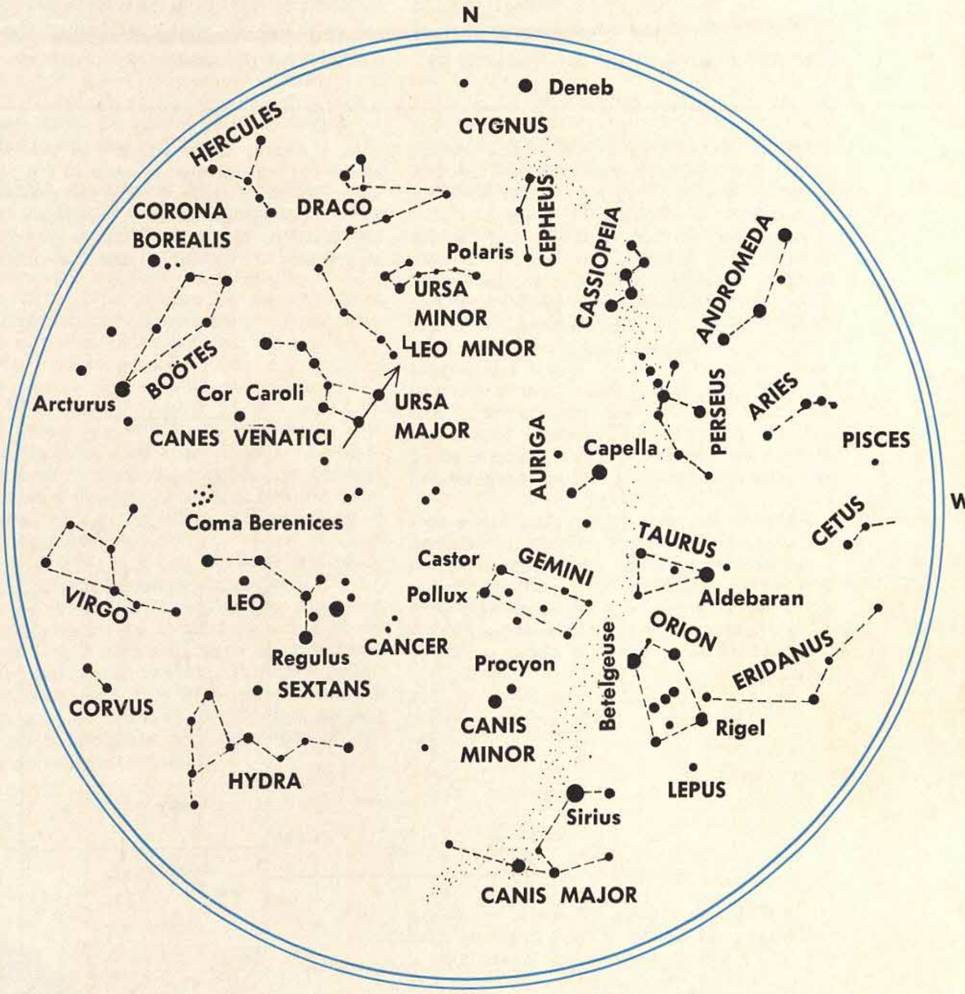
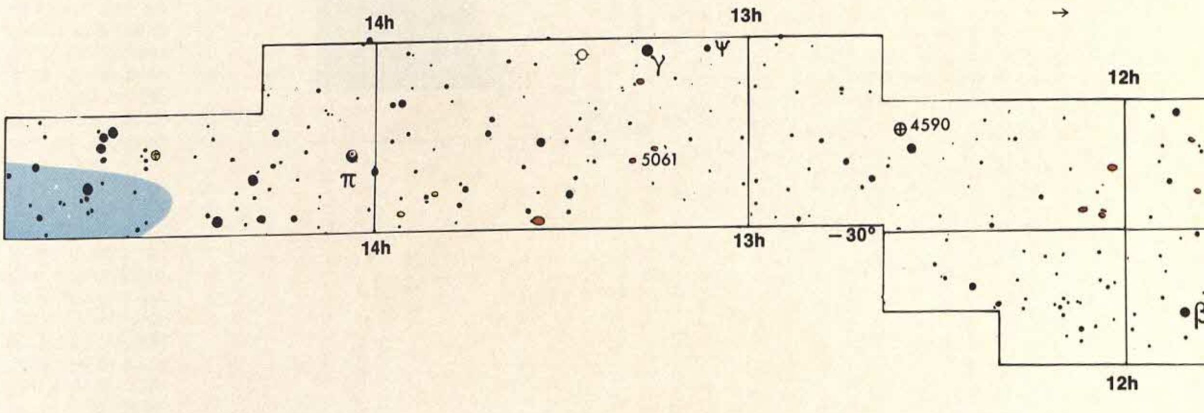


THE MARCH SKY—This map of the March sky shows approximate positions of the principal constellations visible during the month with respect to the horizon and the four cardinal points. At 9:00 P.M. Ursa Minor (the Little Bear) is still high above the northwest horizon. Part of the constellation Draco (the Dragon) extends beneath Ursa Minor. The constellation Boötes (the Herdsman) has already risen; quite low on the horizon, Corona Borealis (the Northern Crown) has made its appearance. Ursa Major (the Great Bear) is about to occupy its highest position in the sky, near the zenith. To the east of these, the small constellation Canes Venatici (the Hunting Dogs) is clearly visible. Further east, fewer stars may be seen. The constellation Leo Minor (the Little Lion) is almost at the zenith, hanging over the constellation Leo (the Lion), which is still high in the sky. To the southeast, near the meridian, is the constellation Hydra (the Sea Serpent); beside it is the constellation Sextans (the Sextant).

Canis Minor (the Little Dog), Canis Major (the Great Dog), and Orion (the Hunter) shine in the southwest sky; Lepus (the Hare) is still visible, although low on the horizon. Taurus (the Bull) is still moderately high on the horizon in the west, and Gemini (the Twins) is near the zenith. Auriga (the Charioteer) is beginning the journey that will soon carry it beneath the horizon in the north. Perseus and Cassiopeia are still visible in the northeast; Andromeda and Aries (the Ram) are quite low on the horizon.



and Gemini are clearly visible above the horizon, but none of them remains long in the sky; with the lengthening of the days, the winter constellations are about to set by the time observations can be begun. Many of the spring constellations are still quite low on the horizon and cannot be observed until late at night.

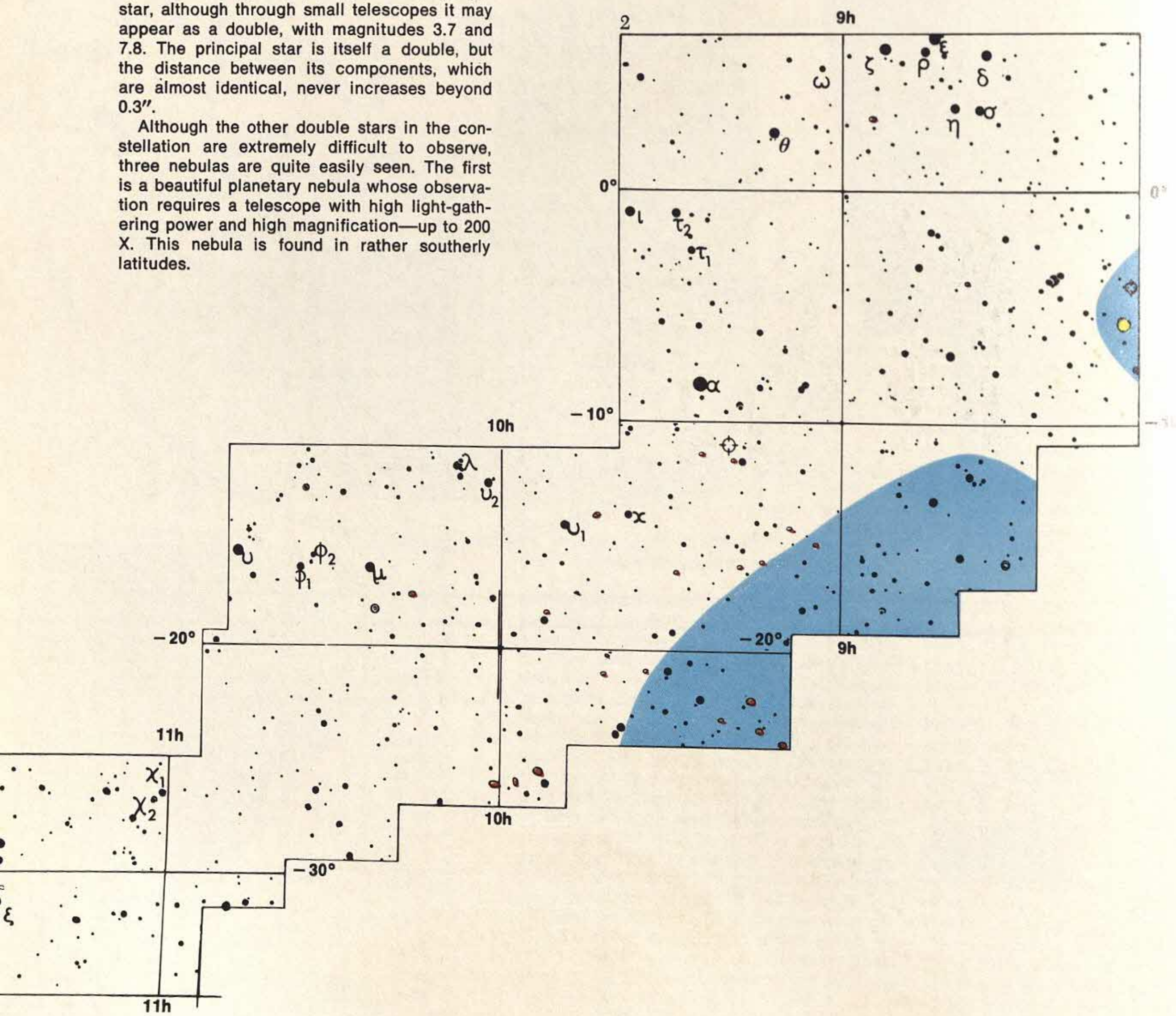
The Milky Way is no longer on the meridian in the position it occupied the previous month, and to the south the sky is sparsely populated with stars and other celestial objects that are readily observable. Nevertheless, the sky is almost clear of cosmic dust, making it possible for an observer to see great distances to where the extragalactic nebulas can be discerned. In this early spring sky, a telescope with a large mirror and very low magnification is most useful for seeking the dim light of the nebulas.

HYDRA—In common with many other constellations that have been drawn near the celestial equator, Hydra extends far into the southern latitudes. As a consequence, many of its interesting double stars, clusters, and nebulas cannot be observed in the middle northern latitudes. Moreover, as is the case with many other spring constellations, the stars that comprise it are not particularly striking.

Among the multiple stars of Hydra, the most remarkable is Epsilon (ϵ). This is a quadruple star, although through small telescopes it may appear as a double, with magnitudes 3.7 and 7.8. The principal star is itself a double, but the distance between its components, which are almost identical, never increases beyond 0.3″.

Although the other double stars in the constellation are extremely difficult to observe, three nebulas are quite easily seen. The first is a beautiful planetary nebula whose observation requires a telescope with high light-gathering power and high magnification—up to 200 X. This nebula is found in rather southerly latitudes.

At a slightly lower latitude, in the region where the constellation extends to the southwest, are two globular clusters that provide an excellent challenge for small telescopes. Number 4590 (p. 127) has no star brighter than magnitude 12; hence, it must be observed through a good telescope on a clear night. Cluster 5061 (p. 127) has a small diameter and is perfectly round; the luminosity at its center corresponds to that of a star of the 10th magnitude. To be studied properly, this cluster requires a telescope with about a 6-in. objective.



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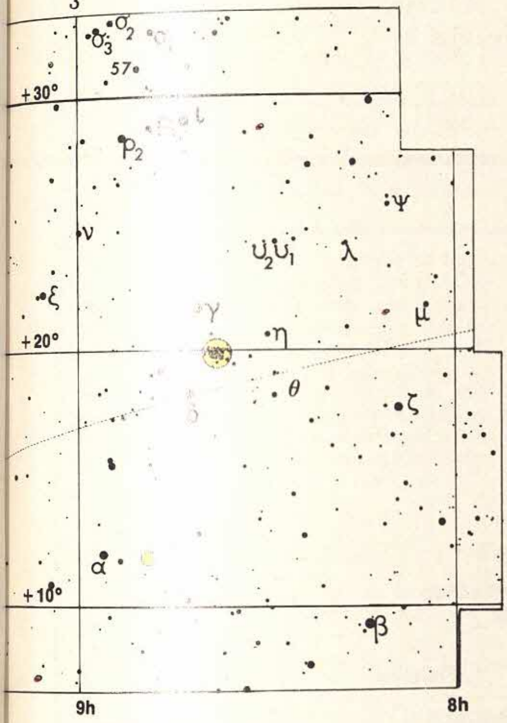

CANCER—This constellation, known as the Crab, is among the least populated with stars; by comparison, even quite small constellations such as Sagitta (the Arrow) and Delphinus (the Dolphin) are much more striking. In addition, Cancer is located between the brilliant stars of Leo and those of Gemini; consequently, to the naked eye the region of the sky in the vicinity of Cancer appears to be almost vacant. The most striking celestial object in the constellation is not a star, but a nebula.

One star of the constellation, Zeta (ζ), is very interesting when viewed through a good telescope, it appears as a triple star. Accurate observation is difficult; a pair of stars is easily seen, along with the third—but this latter is actually another pair of stars extremely close together. The three apparent stars (of about the 5th magnitude) are clearly visible, but the closer pair, separated by only 0.51″, are less discernible; this pair is about 5″ distant from the others.

Another beautiful double star is Iota (ι). Its component stars are of magnitudes 4 and 6.5, and because they are about 30.5″ apart, they can be seen with a telescope of low power. Still another double is number 57, whose component stars, separated 1.5″, are of magnitudes 5.9 and 6.4. Observation of this double star requires a telescope with an objective whose diameter is at least 10 cm (about 4 in.).

Cancer contains two marvelous star clusters, both open or galactic clusters. The most striking is Praesepe, which has been known since antiquity, for it is apparent to the naked eye on extremely clear nights; to the unaided eye, however, the cluster appears as a large spot of light. Galileo was the first to observe the individual stars—with his small telescope, he was able to pick out 36 of them. Today many more can be seen, but, because of the extent of the cluster, only a wide-field telescope can contain it all. Correct values are 15 X for a telescope with a 10-cm (about 4-in.) objective and 25 X for a 15-cm (about 6-in.) objective.

A second galactic cluster, extremely rich in stars, is found slightly below Praesepe, as seen on the chart. Not as easy to observe as Praesepe, this cluster contains about 200 stars ranging from the 10th to the 15th magnitudes. To observe even the brightest of them, an observer must use a telescope with at least a 6-cm (about 2.5-in.) objective; he must use a 50-cm (about 20-in.) telescope to observe the faintest stars. Binoculars serve to locate the cluster in the sky.

SEXTANS—Sextans is the constellation bordered by Hydra, Leo, and Crater (the Cup). Until the year A.D. 1600, no astronomer thought its weak stars worthy of attention; hence, they were never described as belonging to any constellation. The German astronomer Johann Hevelius first gathered the stars into a configuration that he called Sextans, the Sextant.

With a small telescope, only eight double stars can be seen in this constellation, and only one, with the number 35, is visible with the unaided eye. Number 35 is a double with components of magnitudes 6 and 7.2, separated by 6.7″. Gamma (γ), which can be seen only with a powerful telescope, has two components, both of magnitude 5.5, but because the distance between them varies between 0.2″ and 0.4″, they can be seen separately from a professional observatory only.

Of the nebulas, 3166 and 3169 are very close together and can be seen easily with a 25-cm (about 10-in.) telescope. Such an instrument can be built by an amateur. The same instrument would also bring 3115 within reach. All these nebulas are extragalactic and, judging from their luminosity, are some tens of millions of light-years distant.

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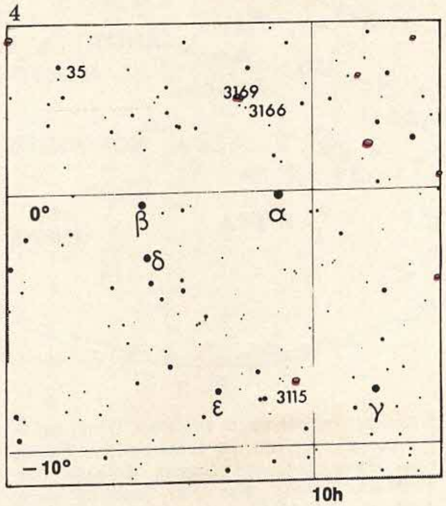

LEO MINOR—The Little Lion is a very small constellation located above the much larger constellation Leo. As with Lynx, Leo Minor is difficult to find with the unaided eye, because its principal stars are quite dim. It is far from the Milky Way; hence the region is sparsely populated with stars and is completely devoid of galactic clusters. A few extragalactic nebulas are present, but they are extremely difficult to observe.

Three double stars are within reach of telescopes of medium power. Star number 31 is a challenge for telescopes with objectives measuring 20 to 25 cm (about 8 to 10 in.); it is composed of two stars of magnitudes 4 and 6.5 located about 0.4″ apart. The powerful instrument is needed because of this small distance. Star number 11 poses a different problem; its two components are 5.8″ apart, a distance that can be resolved with a 60-mm (about 2.5-in.) objective. However, the secondary star is of the 14th magnitude, and the primary star is of magnitude 5.5. This means that a telescope of 25- or 30-cm (about 10- or 12-in.) diameter is needed.

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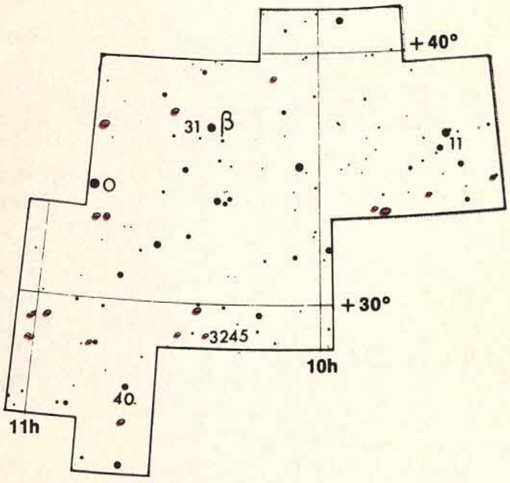

A similar problem is posed by star number 40, which comprises a star of the 6th magnitude and another of the 13th magnitude, located more than 10″ apart. Here again, even an instrument of low magnification must be powerful to capture the dim light of the secondary star.

Of the nebulas shown on the chart, only 3245 is bright enough to be clearly visible in a telescope, and it is extremely weak. Its central part has the luminosity of a star of the 11th magnitude.

THE SKY IN APRIL | Ursa Major, Crater, Leo, and Corvus

The location of the Milky Way during the various seasons of the year is the key to celestial observation. In summer and winter, it is on the meridian—approximately between due south and the zenith. During these seasons, the sky is crowded with easily observed celestial objects—nebulas, galactic clusters, and double stars. In spring and autumn, on the other hand, the sky appears darker and less populated with stars.

Spring and autumn nevertheless have

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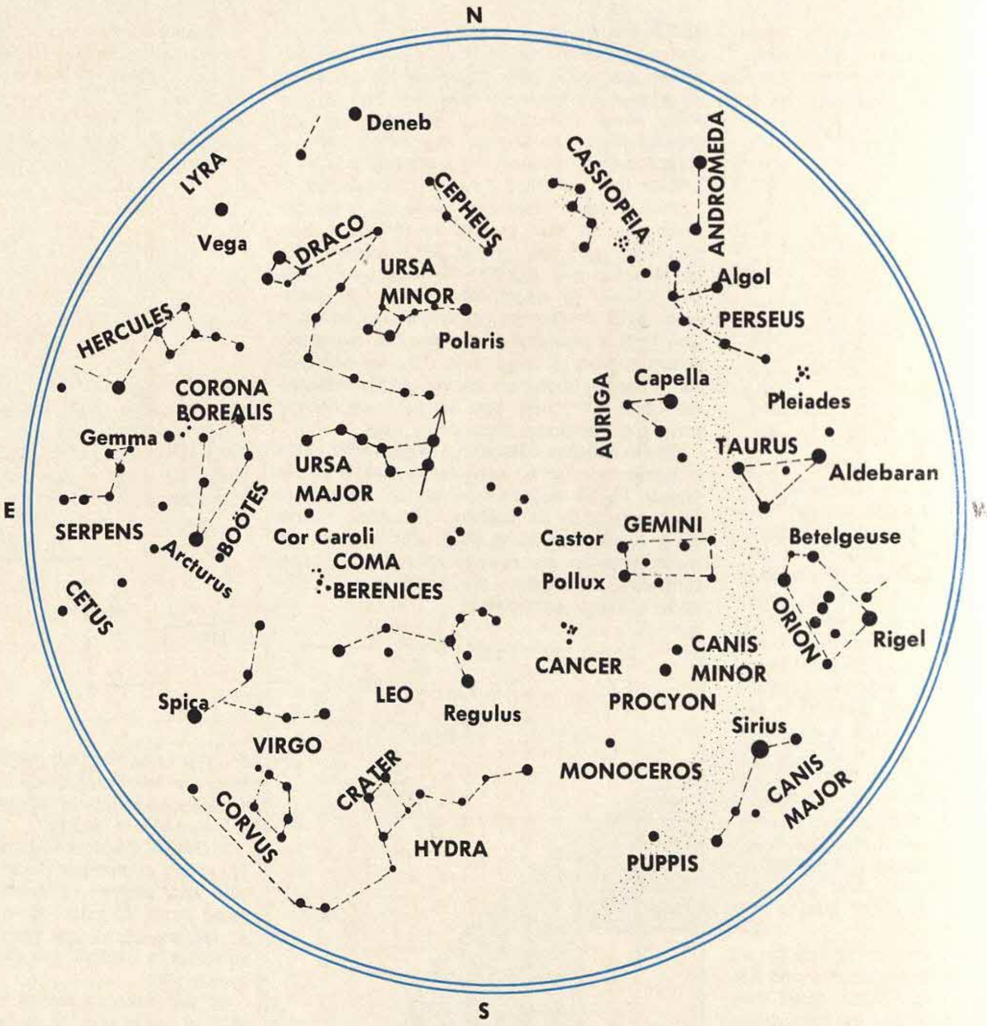


THE APRIL SKY—At nine o'clock on an April evening, few stars can be seen in the arc from the south to the northeast; between northeast and north, however, two prominent stars that remain in the sky through the entire summer and early autumn can be found. These stars, Vega and Deneb, are respectively the principal stars of the constellations Lyra (the Lyre) and Cygnus (the Swan). Still low on the horizon, they are best observed at a later hour of the night.

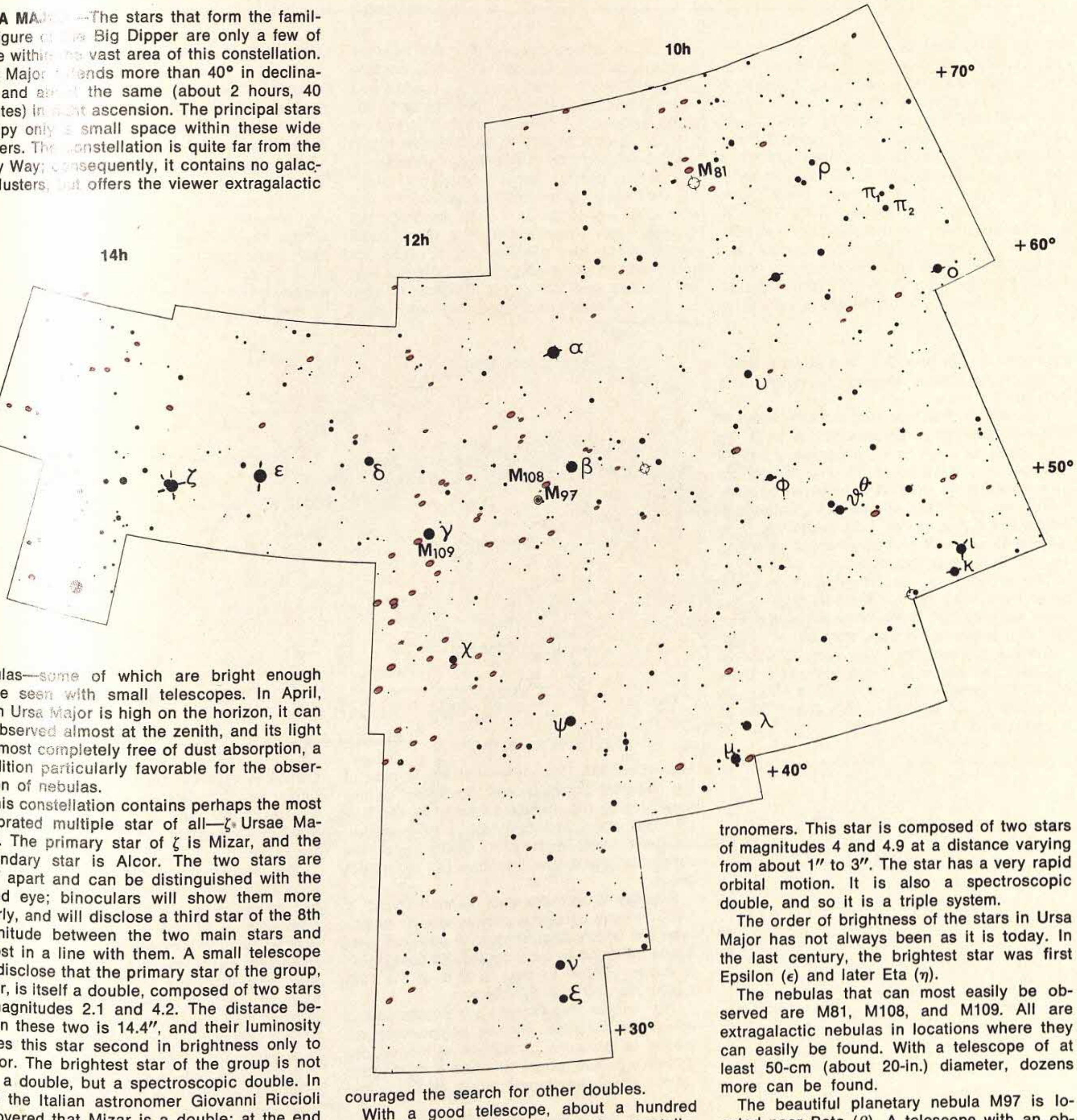
To the east, also low on the horizon, the constellations Cetus (the Whale) and Serpens (the Serpent) are rising. The constellations Hydra (the Sea Serpent) and Corvus (the Crow) are farther south and west. Dominant in the eastern sky are the constellations Boötes (the Herdsman) and Corona Borealis (the Northern Crown), with their beautiful stars, Arcturus and Gemma. In the southeast, the zodiacal constellation Virgo (the Virgin) is already high in the sky; Spica, the principal star, situated in the lower part of the constellation, is still low. The small stars of the constellation Draco (the Dragon) are in the northeast. Ursa Major (the Great Bear) is near its highest point in the sky.

The meridian contains striking constellations. At the zenith is Ursa Major; midway to the southern horizon is Leo (the Lion) with its characteristic diamond shape; Crater (the Cup) is next and then, nearest the horizon, lies Hydra (the Sea Serpent), with its long tail dragging across the meridian. Because of its distinct, narrow, diagonal shape, Hydra takes a long time to cross the meridian in its various declinations.

The fascinating winter train of Orion (the Hunter) is still visible in the west—Taurus, Auriga, Gemini, Canis Minor, Canis Major, and Orion at the center. To the northwest, Andromeda is setting and Cassiopeia and Perseus stand low on the horizon.

much to offer. Far from the Milky Way, the sky is more transparent than it is during the winter and summer, because it is not obscured by the interstellar material of the Galaxy, and the farthest extragalactic nebulas can be seen.

Nebulas can be found in the April sky simply by pointing the telescope randomly in the general direction of certain areas. Other observations may be conducted in determined positions of the sky. The April weather is generally warm enough to allow prolonged observations. Rainy nights are interspersed with clear ones; clear, windless nights are suitable for observing the planets and the double stars, and clear but windy nights provide an excellent opportunity for observing nebulas and other celestial objects that can be seen with telescopes of low magnification.



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URSA MAJOR—The stars that form the familiar figure of the Big Dipper are only a few of those within the vast area of this constellation. Ursa Major extends more than 40° in declination and almost the same (about 2 hours, 40 minutes) in right ascension. The principal stars occupy only a small space within these wide borders. The constellation is quite far from the Milky Way; consequently, it contains no galactic clusters, but offers the viewer extragalactic nebulas—some of which are bright enough to be seen with small telescopes. In April, when Ursa Major is high on the horizon, it can be observed almost at the zenith, and its light is almost completely free of dust absorption, a condition particularly favorable for the observation of nebulas.

This constellation contains perhaps the most celebrated multiple star of all—ζ Ursae Majoris. The primary star of ζ is Mizar, and the secondary star is Alcor. The two stars are 11.5′ apart and can be distinguished with the naked eye; binoculars will show them more clearly, and will disclose a third star of the 8th magnitude between the two main stars and almost in a line with them. A small telescope will disclose that the primary star of the group, Mizar, is itself a double, composed of two stars of magnitudes 2.1 and 4.2. The distance between these two is 14.4″, and their luminosity makes this star second in brightness only to Castor. The brightest star of the group is not only a double, but a spectroscopic double. In 1650 the Italian astronomer Giovanni Riccioli discovered that Mizar is a double; at the end of the nineteenth century, it was the first double to be photographed successfully. It was also the first spectroscopic double to be discovered in the sky, and its discovery encouraged the search for other doubles.

With a good telescope, about a hundred other stars can be observed in the constellation. One worthy of attention is Xi (ξ); it is the first double whose true orbit (as opposed to its apparent orbit) was calculated by astronomers. This star is composed of two stars of magnitudes 4 and 4.9 at a distance varying from about 1″ to 3″. The star has a very rapid orbital motion. It is also a spectroscopic double, and so it is a triple system.

The order of brightness of the stars in Ursa Major has not always been as it is today. In the last century, the brightest star was first Epsilon (ε) and later Eta (η).

The nebulas that can most easily be observed are M81, M108, and M109. All are extragalactic nebulas in locations where they can easily be found. With a telescope of at least 50-cm (about 20-in.) diameter, dozens more can be found.

The beautiful planetary nebula M97 is located near Beta (β). A telescope with an objective of at least 10 cm (about 4 in.) and a magnifying power of at least 100 X is required to observe it.

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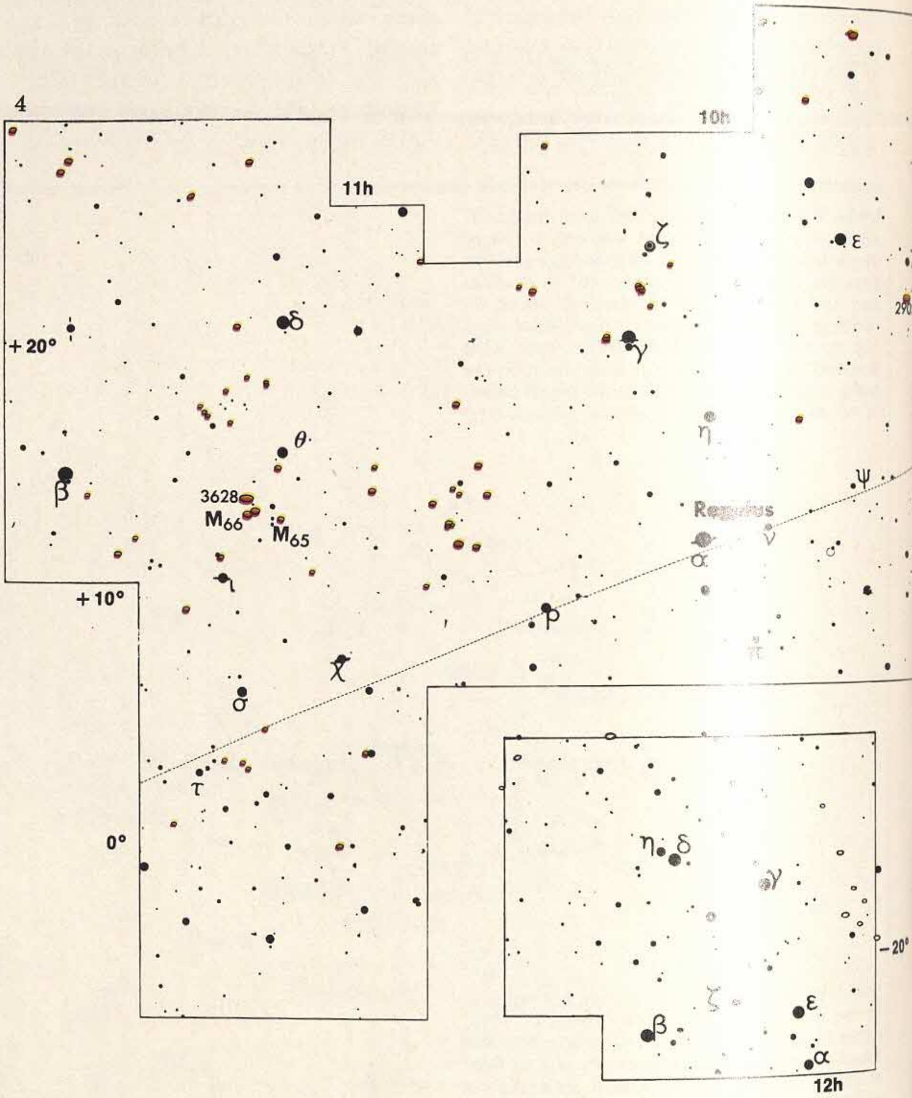

CRATER—Crater, the Cup, is a small constellation at the side of Hydra; like Hydra, it is deficient in stars.

The only double star that is easily seen in this constellation is Gamma (γ); it is of the 4th magnitude and has a companion of magnitude 9.5 at a distance of 5″. The binary Iota (ι) is much more difficult to observe because the companion of the primary star (which is of magnitude 6.3) is of the 12th magnitude; it is difficult to see with an instrument of less than 15-cm (about 6-in.) diameter.

The difficulty of observing Psi (Ψ), on the other hand, derives from the fact that its two stars are only 0.6″ apart. Their luminosity presents no problems because they are of magnitudes 6.4 and 6.9. Relatively easy to observe is Theta (θ), which is directly opposite Delta (δ) in the lozenge they form with ι and ϵ; its components are of magnitudes 6 and 10.5 at a distance of 3.7″.

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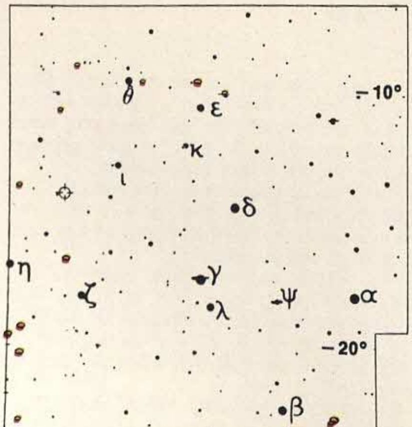


LEO—Leo, the Lion, is one of the largest of the zodiacal constellations; its figure is recognizable by the trapezoid formed by the four principal stars. The brightest is Regulus (α), situated almost exactly on the ecliptic; the second brightest star, Denebola (β), is farthest away.

Regulus is a triple star; located about 3′ from the primary star is another star of magnitude 8.4, which, seen through a powerful telescope, is found to be a double. Its companion is rather difficult to see, as it is of the 13th magnitude and only 2.7″ away.

The double star Gamma (γ) is outstanding in the constellation. Its two components are almost of the same brightness, of magnitudes 2 and 3.5, and about 3″ distant from each other. One of the stars is yellow, and the other is red.

Among the easiest extragalactic nebulas to observe are those identified on the chart as 2903, 3628, M65, and M66.

CORVUS—Corvus, the Crow or Raven, is another small constellation, extending to the right of Crater. Although most of its stars are practically invisible to the naked eye, four stand out.

The double star Delta (δ) is within range of the smallest telescopes inasmuch as its two components are a full 24″ apart; its primary star is of the 3rd magnitude and the secondary of magnitude 8.5.

Another easily observed star is in the northeast, aligned with ϵ and δ. It consists of two stars of identical brightness (magnitude 6.5), situated 5.4″ distant from each other. Spectroscopic observation has indicated that this star is a quadruple system.

A planetary nebula of considerable size lies within the quadrangle of Corvus, almost at the intersection of the diagonals ϵ-δ and β-γ. It can be seen with a small telescope, but its structure cannot be studied without a more powerful instrument.

THE SKY IN MAY | Ursa Minor, Canes Venatici, Coma Berenices, and Virgo

The southern horizon of the May sky is distinguished by celestial areas extremely rich in extragalactic nebulas. They are most numerous in the constellation Virgo (the Virgin), where at least a hundred are visible through small telescopes.

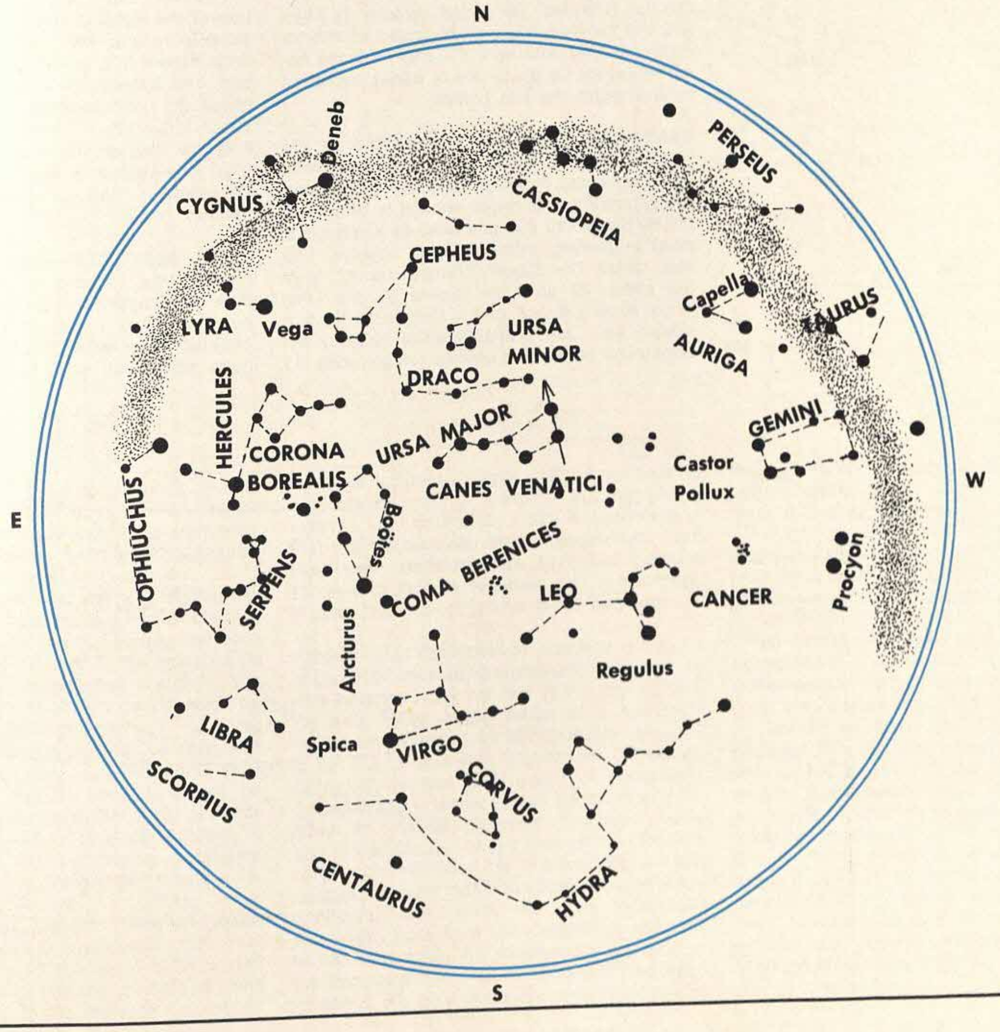
The celestial objects discussed in this article are those most easily observed during May with small instruments—above all, the double stars, which are extremely interesting because of their great variety.

THE MAY SKY—The constellations that will brighten the summer sky appear on the eastern horizon during May. With them rises the summer branch of the Milky Way. The Milky Way lies low on the horizon at nine o'clock in the evening, but by midnight, it can be seen quite clearly, and it remains visible almost until sunrise. To the north-northeast shine stars (such as those of the constellations Cygnus and Lyra) that, because of their nearness to the celestial pole, have remained only briefly beneath the horizon. The constellation Cepheus lies between the pole and the horizon, and some of the stars of Draco (the Dragon) are seen above Lyra (the Lyre). Ursa Minor is between the pole and the zenith, in the best position of the year for telescopic observation. The positions of Ursa Minor (the Little Bear) and Ursa Major (the Great Bear) indicate the season of the year; Ursa Minor pointing to the zenith signifies the middle of spring.

Hercules, Serpens (the Serpent), and Ophiuchus (the Serpent-Bearer)—three typical summer constellations—are found in the east. To the southeast is the constellation Libra (the Scales). For a few hours of the night some of the stars of the northern part of Centaurus (the Centaur) appear above the horizon; they may be observed during the later hours of the night when they are high in the sky.

Ursa Major is still near the zenith; Boötes (the Herdsman) and Corona Borealis (the Northern Crown) are also quite close to the zenith. Virgo, Canes Venatici (the Hunting Dogs), and Coma Berenices (Berenice's Hair) are found on the meridian.

To the west some of the winter constellations may still be seen. Orion has set, but Taurus, Gemini, and Canis Minor are still on the horizon. Leo remains high in the sky, but Auriga and Perseus in the north are about to set. Capella skims the horizon, or slips beneath it for an hour at the most; in the summer, it is so close to the horizon that atmospheric interference obscures its light.



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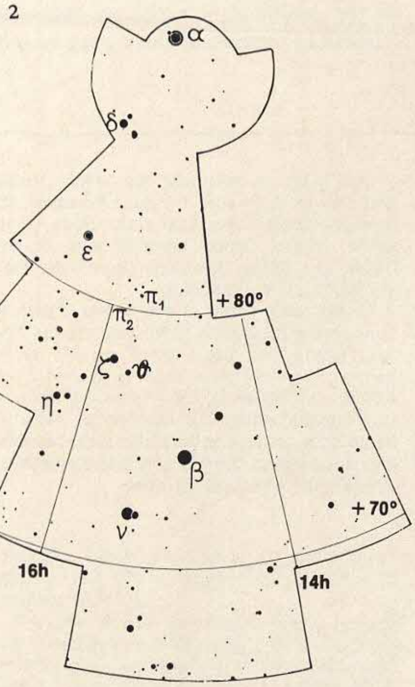

URSA MINOR—The only notable star in this constellation is Polaris (α), the Pole Star. At the present time it is no more than a single degree away from the north celestial pole; in the year 2095, because of the precession of the equinox, the distance will have decreased to only 26′.

The Pole Star is a beautiful double; the primary star is of the 2nd magnitude and the secondary star of the 9th magnitude, with the distance between the two 18.3″. It can be observed as a double through a telescope with a 40-mm (1.5-in.) objective and a magnification of 50 X. It is particularly easy to observe, because it remains practically stationary in the sky; once a telescope is trained on it, it is not necessary to follow the star.

Another easily observed double star is Pi_1 (π_1), whose components are of magnitudes 6.1 and 7 separated 30.1″. The components of its companion Pi_2 (π_2) are of magnitudes 7.1 and 8.1 at a distance of 0.7″; because of this closeness, a good telescope of 15 to 20 cm (about 6 to 8 in.) is required to observe this double. However, its orbital velocity is high, and the components may be found at shorter distances—as little as 0.1″—and even the finest telescope in the world is barely sufficient to distinguish the two bodies.

CANES VENATICI—The constellation of the Hunting Dogs is small, but it contains many easily observed celestial objects. A single star, the principal (α), is bright enough to be picked out by the naked eye and used as a reference point in seeking other celestial objects. This star, called Cor Caroli (Charles' Heart), is at the center of an arch formed by the Ursa Major stars γ, δ, ϵ, ζ, and η. Cor Caroli (α) is a double star, easily distinguished both by the brightness of its components (magnitudes 3.7 for the primary and 5.7 for the secondary) and by their great separation (19.9″). A small instrument with a 50-mm (about 2-in.) lens will show the star as a double. This constellation contains 30 more double stars, none of them conspicuous enough to be found easily in the sky or to be resolved with a small telescope.

Canes Venatici contains two other interesting formations, a globular star cluster and a bright extragalactic nebula. The globular cluster is located between Cor Caroli and Arcturus in the constellation Boötes, somewhat nearer the latter. A telescope of at least 15 cm (about 6 in.) is required for its observation. Its total luminosity is that of a star of the 7th magnitude, while its size is quite large, covering about 0.25°. Its distance is 12,000 light-years. The 25 most luminous stars in its center are of magnitude 14.5. The spectacle of these stars shining against the nebulous light of the many tens of thousands of individually invisible stars that make up the background is quite fascinating.

The other exceptional body in the constellation of the Hunting Dogs is the double extragalactic nebula M51. From the larger part, arms extend in a spiral to envelop the smaller part. The distance between the two nebulas is about 6′; the dimensions of the group are about 6′ by 12′. A small telescope will show only the neighboring nuclei of the two nebulas; a telescope of medium power will show the gaseous ring surrounding the principal nebula.

COMA BERENICES—This is another small constellation, extending between Leo and Boötes. It contains no particularly bright stars, but the group of which Gamma (γ) is the brightest is a galactic cluster. Its stars are quite close and, even though they are faint,

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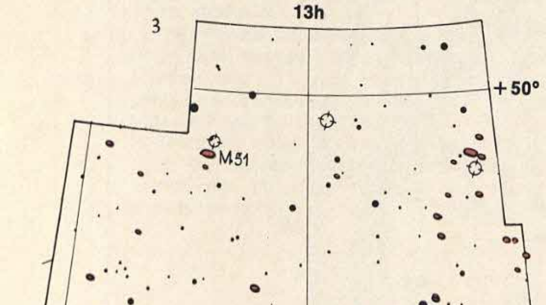

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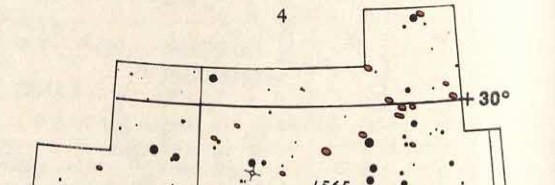
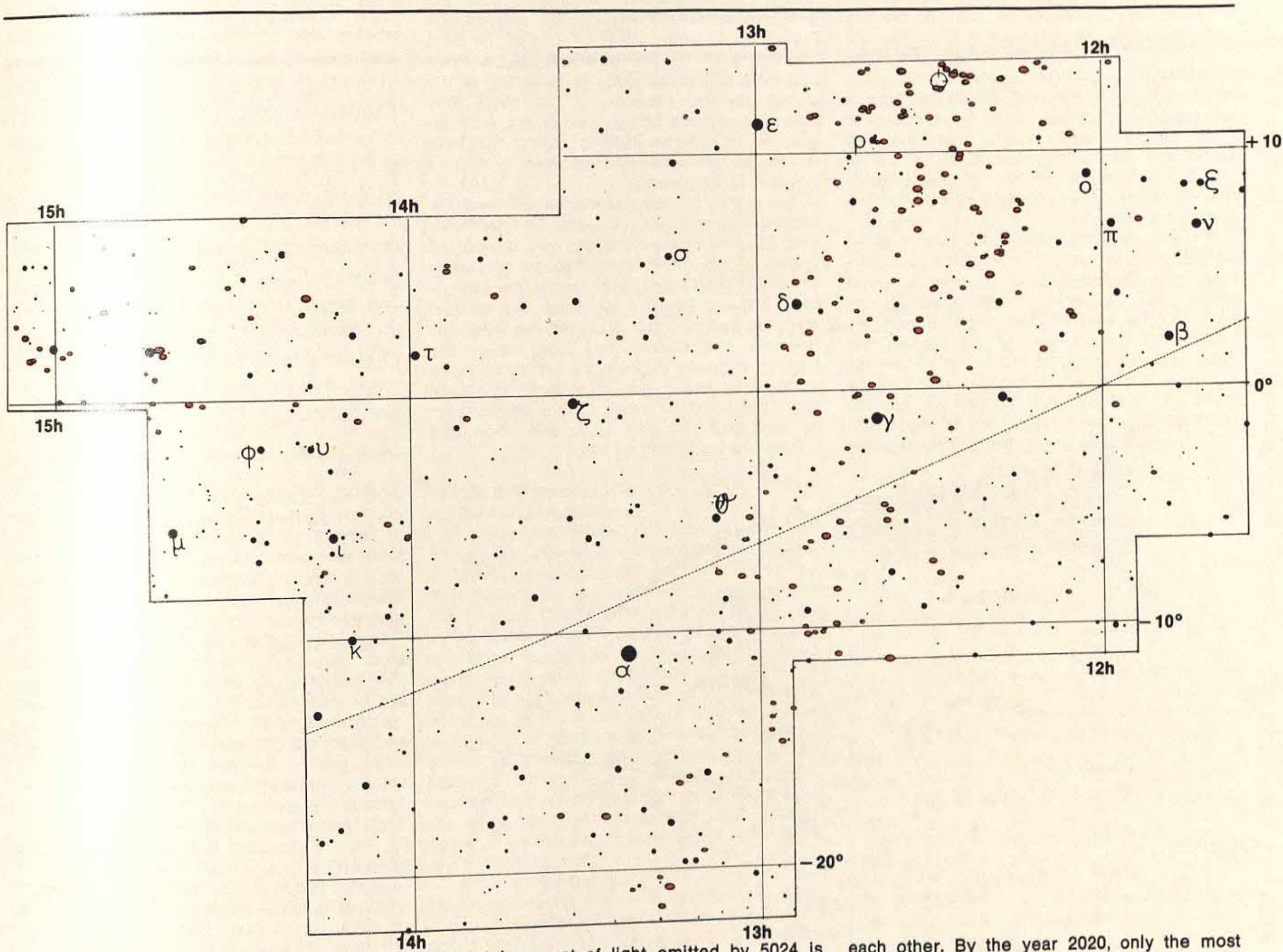




together they offer quite a luminous spectacle. In addition to these stars—which can be seen even with low-powered binoculars—the constellation is rich in extragalactic nebulas and contains two globular clusters.

The double stars are difficult to observe. With a telescope of at least 70 mm (about 3 in.), an observer can see the double indicated on the map by the number 2; the components of this double have magnitudes 6 and 7.5 and lie 3.7″ apart. Others shown on the map require more powerful instruments.

Two extragalactic nebulas can be seen with small instruments; they are 4565 and 4826 (near the triple star 35, which cannot be viewed with a small instrument). The first has an extension of about 15′ (half the diameter of the full moon); the second is somewhat smaller, but visible in an instrument with a 10-cm (about 4-in.) objective.

The two globular clusters, 5024 and 5053, are faint and difficult to see, despite their considerable size. The diameter of 5024 is half that of the full moon, and the diameter of 5053 is one fourth that of the full moon; however, the total amount of light emitted by 5024 is equivalent to that of a star of 9th magnitude, and the light emitted by 5053 is equivalent to that emitted by a star of 11th magnitude. Even the most luminous stars in these globular clusters cannot be reached with a telescope of less than 15-cm (about 6-in.) diameter.

VIRGO—This constellation contains within its boundaries as many extragalactic nebulas as may be seen in all the rest of the sky—counting only those within range of a telescope having an objective of 20 to 30 cm (about 8 to 12 in.) in diameter. Except for this abundance of nebulas and a pair of noteworthy double stars, however, Virgo offers little of interest to amateur observers. The first double star is Gamma (γ), whose two components are very bright—both of the 3rd magnitude—and revolve around a common center of gravity approximately once every 180 years; thus in 90 years they pass from their maximum distance to their minimum. The maximum elongation of the two stars occurred in 1930 and amounted to about 6″; now the stars are approaching each other. By the year 2020, only the most powerful telescopes will be able to resolve them at a distance of 0.3″ to 0.5″.

At 7″ from Theta (θ), which is of the 4th magnitude, is a companion of the 9th magnitude. It is relatively easy to distinguish this double star with a telescope having a 70-mm (about 3-in.) lens.

The region of the sky that is rich in bright extragalactic nebulas extends from Coma Berenices across the region to the right of Epsilon (ε); it then descends in the direction of Gamma (γ) as far as Alpha (α), Spica. The region bounded by ε Virginis, γ Virginis, and β Leonis was named the Lair of the Howling Dogs by ancient Arab astronomers. This region has a maximum density of extragalactic nebulas. A telescope equipped with minimum magnification will bring hundreds of nebulas into view, but it is difficult to distinguish the points of interest in each of them with a small instrument. Because of their great distance, these nebulas are barely perceptible as spots of identical dimension, differing from one another only in brightness.

THE SKY IN JUNE | Boötes, Corona Borealis, Libra, and Serpens

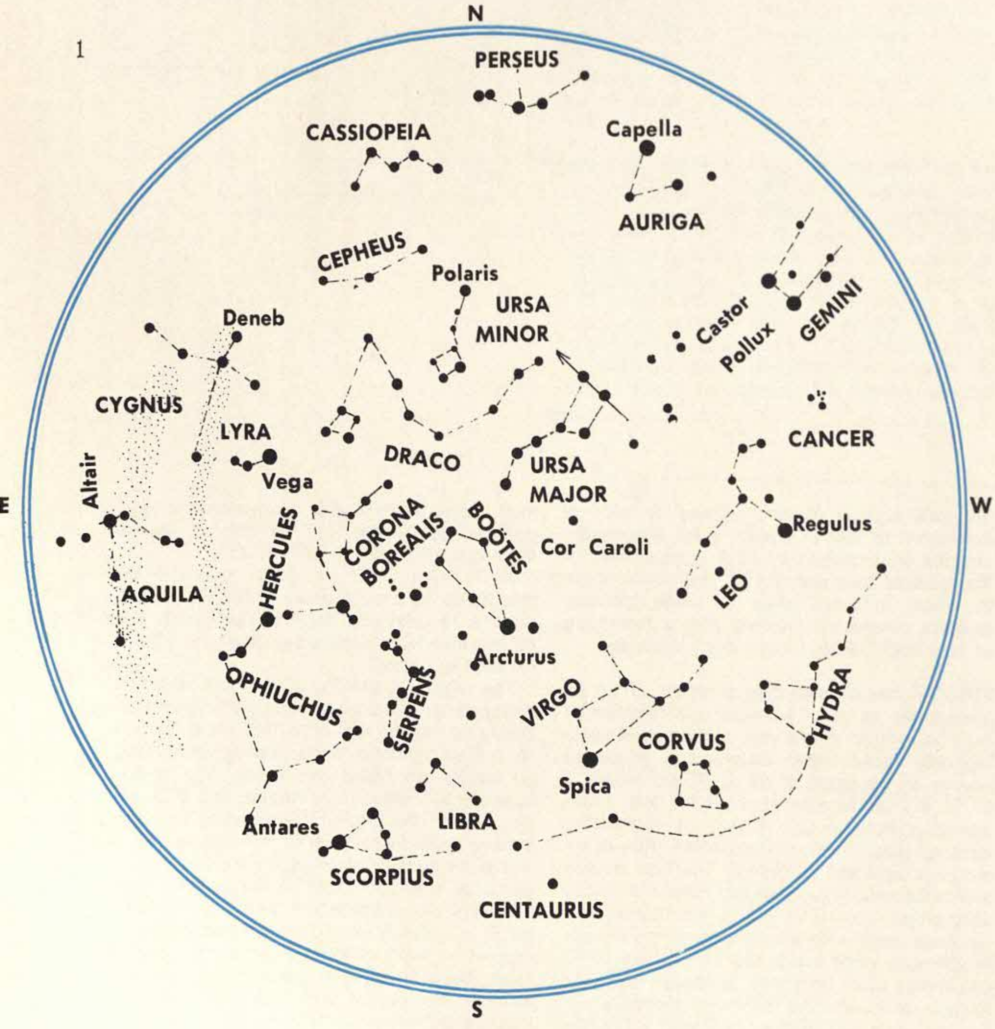
THE JUNE SKY—On the northern horizon, the constellation Cassiopeia is low in the sky under the Pole Star. Above it is Cepheus, and to the east is Cygnus (the Swan). The rising constellation Aquila (the Eagle) is visible low on the horizon to the east, mainly because of its beautiful principal star, Altair. Between Altair and the zenith, Vega illuminates the whole sky. Hercules is almost at the zenith, and Boötes (the Herdsman), Corona Borealis (the Northern Crown), and Libra (the Scales) are on the meridian.

Ancient mythology placed the serpent of the constellation Serpens in the hands of Ophiuchus (the Serpent-Bearer) to form a single group; thus, the serpent appears both to the east and the west of Ophiuchus. During this month, the western part of the serpent, the head, is on the meridian; in a month or less the tail, now in the east, will have moved to the meridian. In June, it is difficult to see the tail until about an hour before midnight.

To the south, the constellation Scorpius (the Scorpion) has already risen in the sky; in the Northern Hemisphere, it is too low on the horizon to be easily observed. One of the most interesting of all the constellations, it rivals and even surpasses Orion in its wealth of celestial objects. Because of the short time Scorpius appears above the horizon, it is rewarding to observe it even during the hour or two of the June evening when it is in a position to be viewed.

The sky in the west seems almost empty in comparison with the abundant constellations that adorned this part of the sky during the spring. Of the winter constellations, only parts of Gemini (the Twins) and Auriga (the Charioteer) remain. Toward the south the modest stars of Cancer (the Crab), Hydra (the Sea Serpent), and Corvus (the Crow) lie on the horizon. Between the southern horizon and the zenith Ursa Major (the Great Bear) is still in sight, beginning its swing toward the northern horizon; and Leo (the Lion) and Virgo (the Virgin) are beginning to set.

This month's sky may be most famous for its "June Moon," but to the amateur astronomer, the return of the Milky Way to the horizon is of much greater interest. The winter branch of the Galaxy, which extended from Auriga through Monoceros to Canis Major, generally offers poor subjects for observation. The constellations of the winter branch contain the most luminous stars visible to the naked eye—the seven stars of Orion, all of the 1st or 2nd magnitude, and the eight stars of the surrounding constellations. In the summer sky, however, even a small telescope suffices to reveal many new and fascinating celestial objects.



BOÖTES—Boötes, the Herdsman, is vast in northern declination, extending from about 55° to about 8°; it is somewhat [illegible] extensive in right ascension. Although [illegible] the Milky Way, it contains few bright extragalactic nebulas, particularly when compared with the concentration of nebulas in the constellation Virgo.

Boötes contains some interesting double stars. Kappa (κ) is easily observed with a 50-mm (about 2-in.) telescope; its components are of magnitudes 5.1 and [illegible] separated by a distance of 12.6″. The two stars are yellow and lilac, but the contrast is not strong. Another easily observed double is Theta (θ), whose components are of magnitudes 4.9 and 7.5 and are located 31.8″ apart; they are distinguishable with any instrument more powerful than binoculars. Still another easily observed double is Pi (π), with components of magnitudes 4.9 and 6, 5.8″ apart. Zeta (ζ), in contrast, is rather difficult to observe; although its components have magnitudes of 3.5 and 3.9, they are separated by only about 1″, and a more powerful telescope is needed to resolve them.

The double stars Delta (δ) and Mu (μ) are easily observed. The former has components of magnitudes 3.2 and 7.4 at a distance of 105″, distinguishable even with binoculars. The latter has components of magnitudes 4 and 6.5 at a distance of 108″.

The most beautiful double in the constellation is Epsilon (ϵ), whose components have magnitudes of 3 and 6.3 and are separated by 2.6″. It is within reach of a telescope having an objective with a diameter of 60 to 70 mm (about 2.5 to 3 in.).

The few extragalactic nebulas of the Herdsman are inaccessible with small telescopes. The only other object that can be sighted with such instruments is the globular cluster 5466 in the southern part of the constellation, but its individual stars cannot be seen. Its combined light (its brightness if its light were concentrated at a single point) is of about the 11th magnitude; its diameter is 9′, about one third that of the moon. Its faintness makes it of interest as a point of celestial geography.

CORONA BOREALIS—The exceptional characteristic of this constellation is that its stars seem to form a crown, with the principal star, Gemma (α), where the main jewel of the crown ought to be. The constellation contains many interesting double stars and some exceptional variables.

The double star Eta (η) is quite difficult to observe because, although it is made up of stars of between the 5th and 6th magnitudes, the distance between them is less than 1″. Gamma (γ) is even more difficult to observe for the same reason. However, Zeta (ζ) is easy to see, even with a 50- to 60-mm (about 2- to 2.5-in.) telescope; its stars are of the 4th and 5th magnitudes, separated by 6″. Sigma (σ), whose components are of the 5th and 6th magnitudes but separated by only 1.4″, is difficult to observe as a double.

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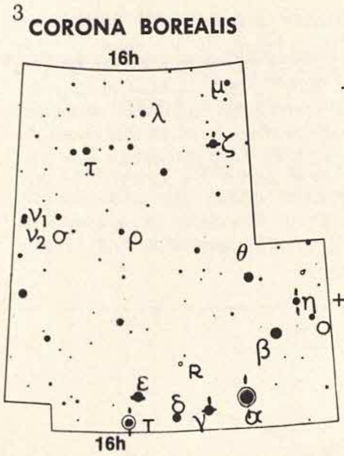

The stars designated Nu₁ and Nu₂ (ν_1 and ν_2) can be seen with low-powered binoculars and sometimes with the naked eye. These two stars are closer to Earth than are Mizar and Alcor in the constellation Ursa Major.

The variable star R is quite interesting, maintaining its brightness for long periods—even months—at about magnitude 5.5; then, it rapidly falls off to magnitude 12.5. In the latter phase, at least a 15-cm (about 6-in.) telescope is required for observation. The star designated T has an unusual characteristic that can be observed through a pair of binoculars; it decreases in luminosity in a brief period from magnitude 2 to magnitude 9.5, then returns again to its former brightness, but with an irregular periodicity.

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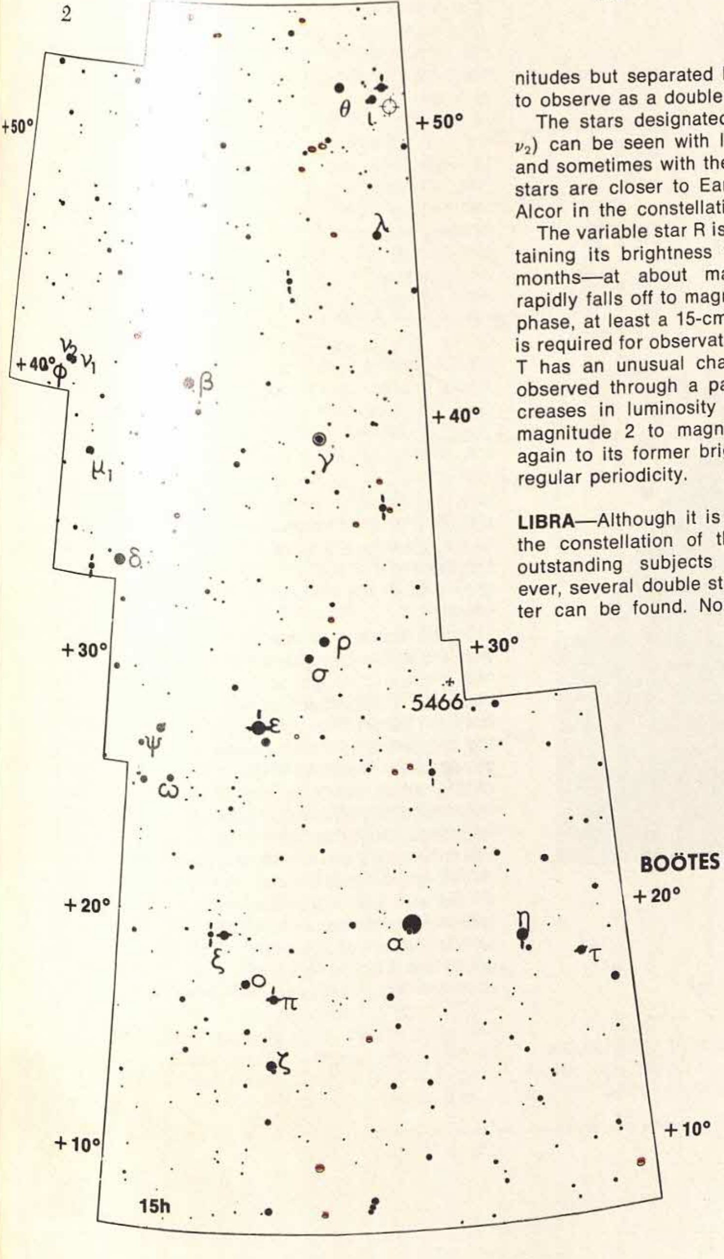

LIBRA—Although it is next to the Milky Way, the constellation of the Scales contains no outstanding subjects for observation. However, several double stars and a globular cluster can be found. None of the extragalactic nebulas, in which the constellation is rich, is within range of small telescopes. Virgo, Libra, and Scorpius are the constellations in which the planets Neptune and Uranus will appear during the next 10 to 20 years. In 1968, the former was found between Eta (η) and Kappa (κ) of Libra. In the same year, Uranus was near Eta (η) of Virgo. Because these planets are so distant from the sun and move slowly, their approximate positions change little in several years.

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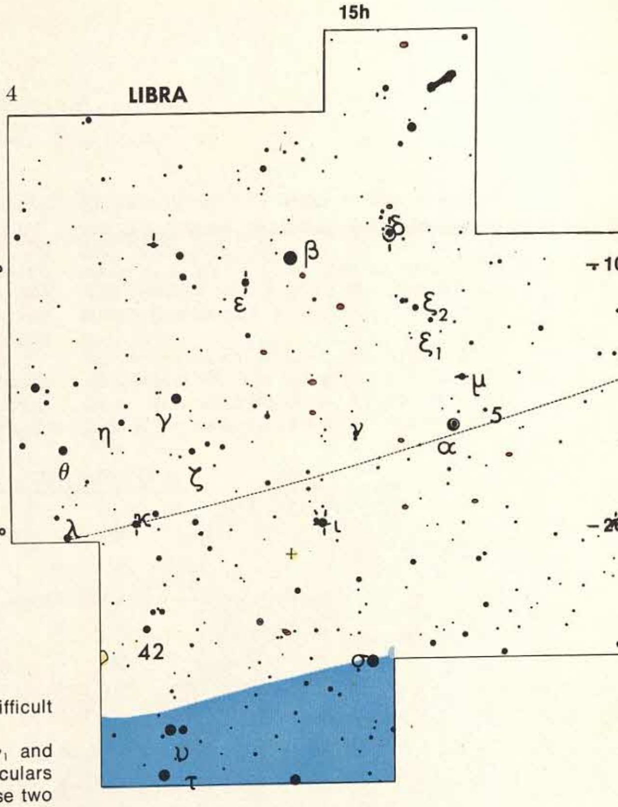

Star 5 can be observed with only moderate difficulty. It is a binary or double with a primary star of magnitude 6.3 and a secondary star of magnitude 11; the components are separated by 2.7″. A 70-mm (about 3-in.) telescope will resolve it. Mu (μ) is composed of stars of magnitudes 5.5 and 6.3 at a distance of 1.5″. A 10- to 15-cm (about 4- to 6-in.) telescope with a high-quality lens (or mirror) is needed to observe it. Alpha (α), comprising stars of the 3rd and 6th magnitudes, can be observed through binoculars. Iota (ι), too, is easily observed; its stars are of the 5th and 9th magnitudes, 57″ apart. Star 42, on the other hand, tests the quality of a 70-mm (about 3-in.) telescope; its stars are of magnitudes 5.1 and 9, separated by only 1.8″.

The constellation's globular cluster contains a great number of stars, but most of them are beyond the reach of a small telescope. To see the cluster clearly, an observer needs an instrument with an objective of 15 to 25 cm (about 6 to 10 in.). It shines a little less brightly than a star of the 10th magnitude. Its apparent diameter is about one third that of the full moon, so that a magnification of only 20 to 30 X will show it fairly well; a larger objective is required if the observer hopes to pick out its more luminous stars, which have magnitudes 13 and 14.

SERPENS—This constellation is bisected by the figure of Ophiuchus. Its western part lies far from the Milky Way, while the eastern part lies exactly on the Galaxy's axis. It is a rich constellation, containing a large globular cluster, a few open clusters, and several double stars.

The double star Delta (δ) is easily observed; its stars are of the 3rd and 4th magnitudes, separated by 2.7″, a distance that a 60- to 70-mm (about 2.5- to 3-in.) telescope can resolve. Another beautiful and easily observed star is Theta (θ), in the tail of the Serpent; it is made up of two stars of magnitudes 4 and 4.2 at a distance of 22.6″. Although they usually appear almost identical in brightness, these two stars sometimes show a difference in magnitude of as much as 1.3, rather than 0.2.

In the western part of the constellation is a beautiful globular cluster with a diameter of about 20″, about two thirds the diameter of the moon. It can be observed through binoculars, for its total brightness is equivalent to that of a star of magnitude 7.1. Isolated stars in the cluster are easily found, because the brightest are of the 11th and 12th magnitudes; it is one of the richest clusters in the firmament.

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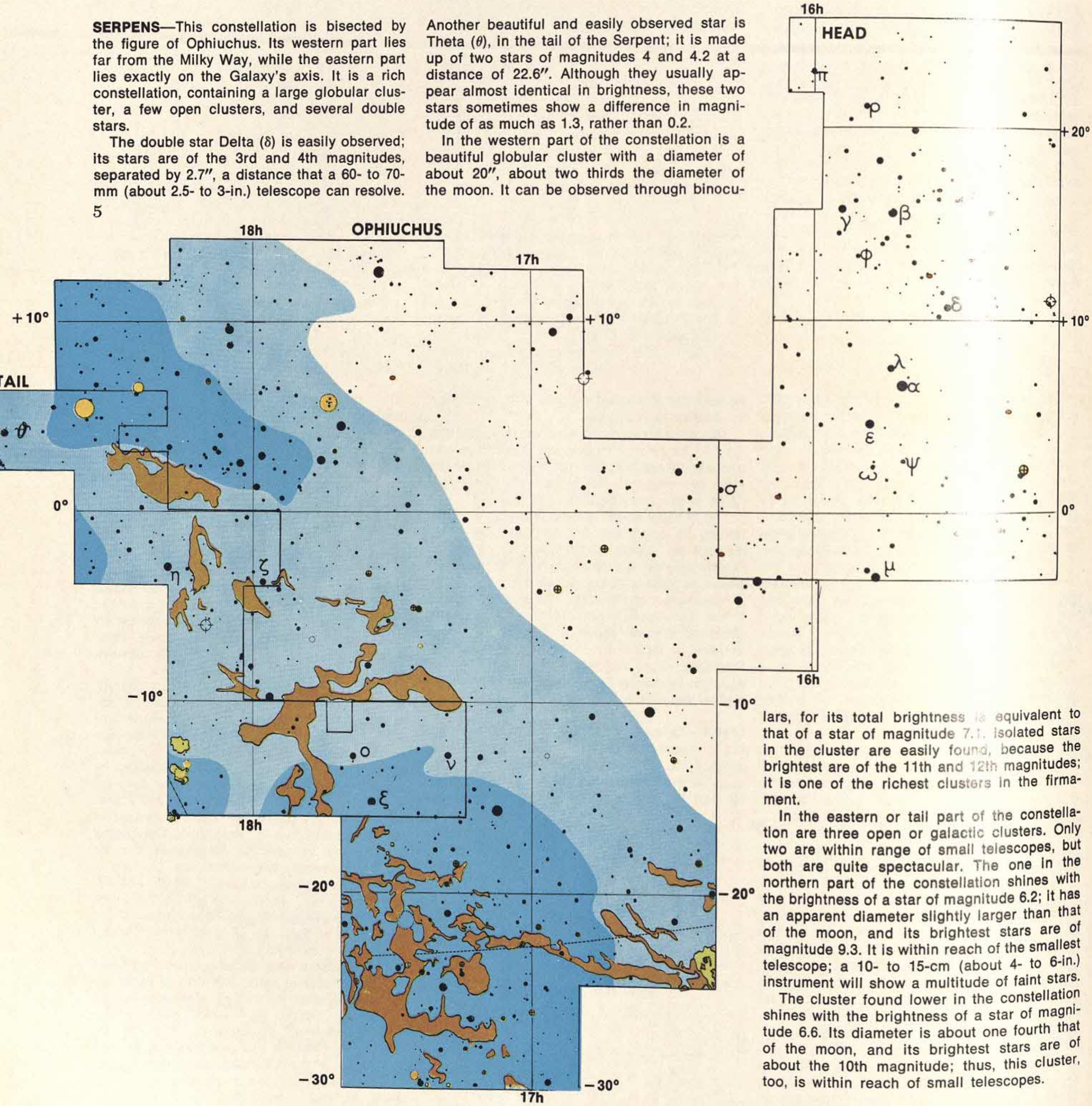


In the eastern or tail part of the constellation are three open or galactic clusters. Only two are within range of small telescopes, but both are quite spectacular. The one in the northern part of the constellation shines with the brightness of a star of magnitude 6.2; it has an apparent diameter slightly larger than that of the moon, and its brightest stars are of magnitude 9.3. It is within reach of the smallest telescope; a 10- to 15-cm (about 4- to 6-in.) instrument will show a multitude of faint stars.

The cluster found lower in the constellation shines with the brightness of a star of magnitude 6.6. Its diameter is about one fourth that of the moon, and its brightest stars are of about the 10th magnitude; thus, this cluster, too, is within reach of small telescopes.

THE SKY IN JULY | Draco, Hercules, Ophiuchus, Scorpius

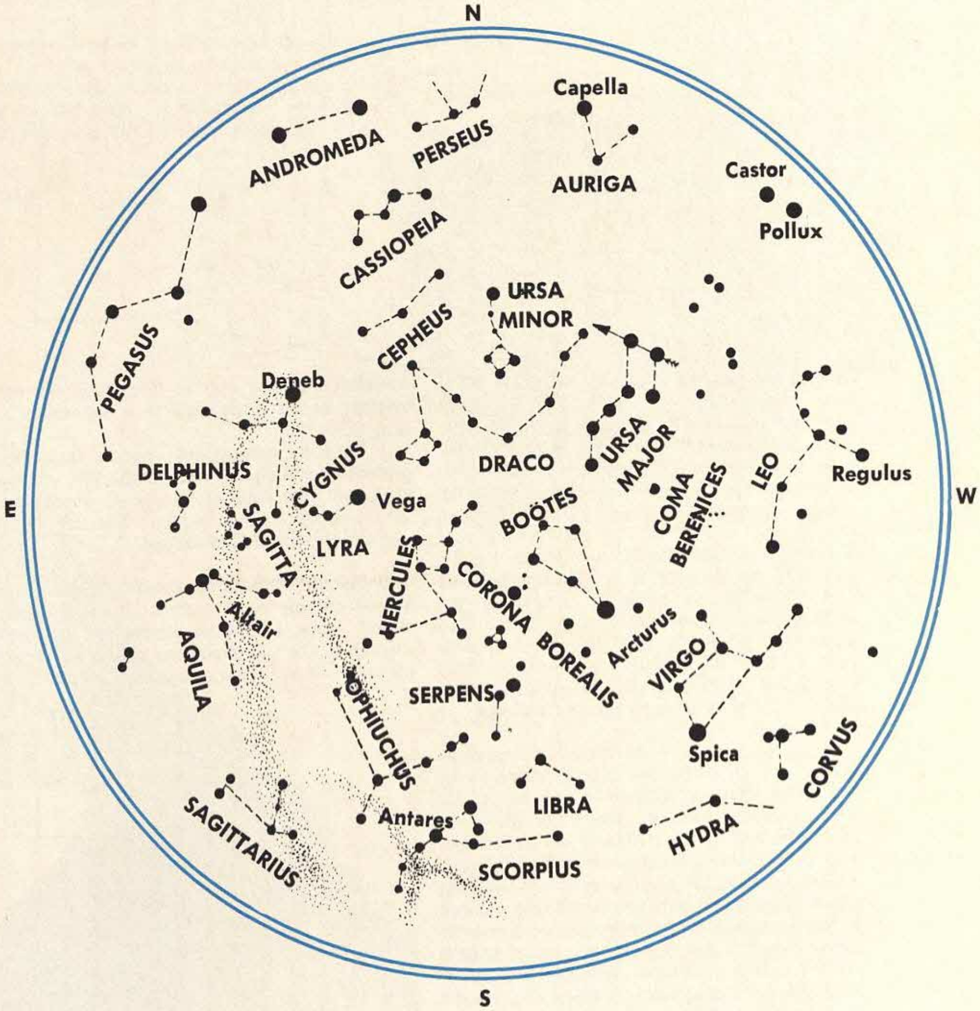
July weather provides the year's best meteorological conditions for observing the sky. Temperatures are high, and the coolness of the night is refreshing. However, an observer at a high altitude must be careful not to use his telescope until the temperature of the telescope and all its components has stabilized; care must also be taken that the difference in temperature at sunset does not cause fogging of the lens.

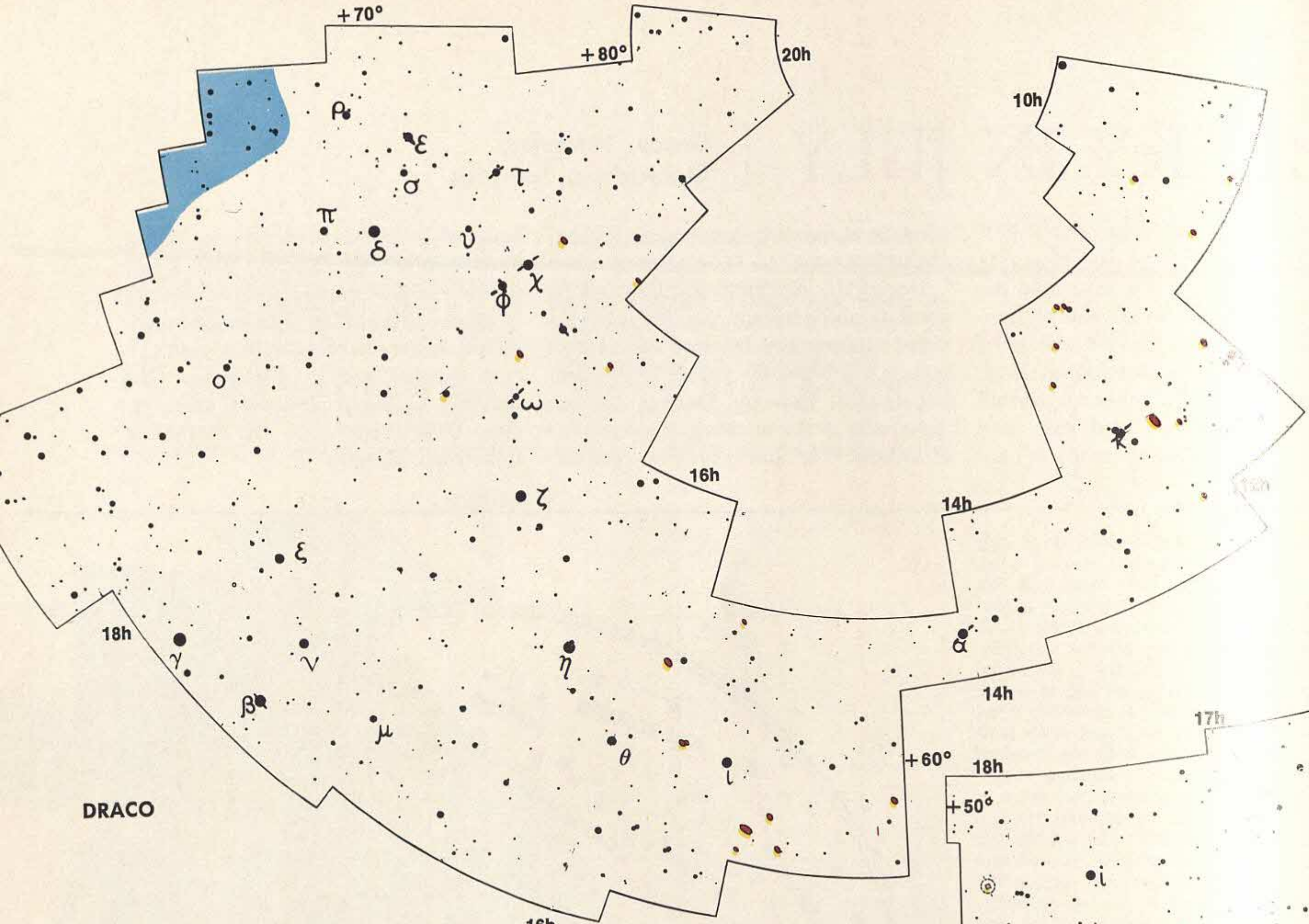
During this month, long nights may be spent in observing the sky, for July provides opportunities for viewing celestial objects not ordinarily visible in succeeding months. However, because the sun rises early in the morning, viewing time is limited. The July sky is a treasure-house of beautiful constellations cloaked in the summer branch of the Milky Way; it is one of the most impressive celestial spectacles. The Milky Way runs through the constellations of Scorpius, Ophiuchus (the Serpent-Bearer), Sagittarius (the Archer), Cygnus, Cassiopeia, and Perseus. It is brightest in the south and split below Cygnus.

THE JULY SKY—At nine o'clock on a July evening (ten o'clock, daylight saving time), the dark sky is covered with many beautiful stars that are easily identified. Vega is almost at the zenith (it will reach the zenith in an hour or two), while Antares and the constellation Scorpius (the Scorpion) are to the south. The calm and relatively bright nights of the summer are the best times for observing these stars. Arcturus is in the west and Altair is in the east. These four stars form the cross of the summer constellations. Although it contains no extremely bright stars, the center of the cross can be found by aligning the end stars, thus locating the weak star α Ophiuchi. To the right of this is α Herculis—easily found through its relation to α Ophiuchi. Beside this star are its other stars of the constellation, among which the globular cluster can be seen with the naked eye. In the west, Virgo (the Virgin) is setting—a reminder of the spring nights when the constellation shone on the meridian. Another of the spring constellations, Leo (the Lion), is about to set, not to be seen again until winter. On the eastern horizon, constellations marking the end of summer are appearing; among them is Cygnus (the Swan), which will be visible on the meridian in succeeding months. Beside it are the small constellations Sagitta (the Arrow) and Delphinus (the Dolphin), both rich in celestial objects and interesting because they lie in the Milky Way. Andromeda and Pegasus command the northeast horizon; together they foretell the arrival of autumn nights, when they will be shining brightly.

To the north, Ursa Major (the Great Bear) is still high in the sky, but its western part is near decline. Cassiopeia is still low on the horizon in the northeast; it rises higher as the night passes. Near the zenith to the north, Draco (the Dragon) dominates the sky; this is quite a large constellation, although it does not contain any particularly bright stars. Finally there is Capella, whose brilliant yellow light skims the horizon, dimmed by the atmosphere. When Capella returns above the horizon within a few months, it will be autumn.

The Milky Way runs through the constellations of Scorpius, Ophiuchus (the Serpent-Bearer), Sagittarius (the Archer), Cygnus, Cassiopeia, and Perseus. It is brightest in the south, and split below Cygnus; observers in southern latitudes can see that the split continues almost to the south pole, beside which the Milky Way passes. On exceptionally clear nights, an observer can sweep the southern horizon with binoculars to obtain a view of some of the most beautiful stars that appear in the southern skies, stars that can be seen only rarely—and then for only a short while.





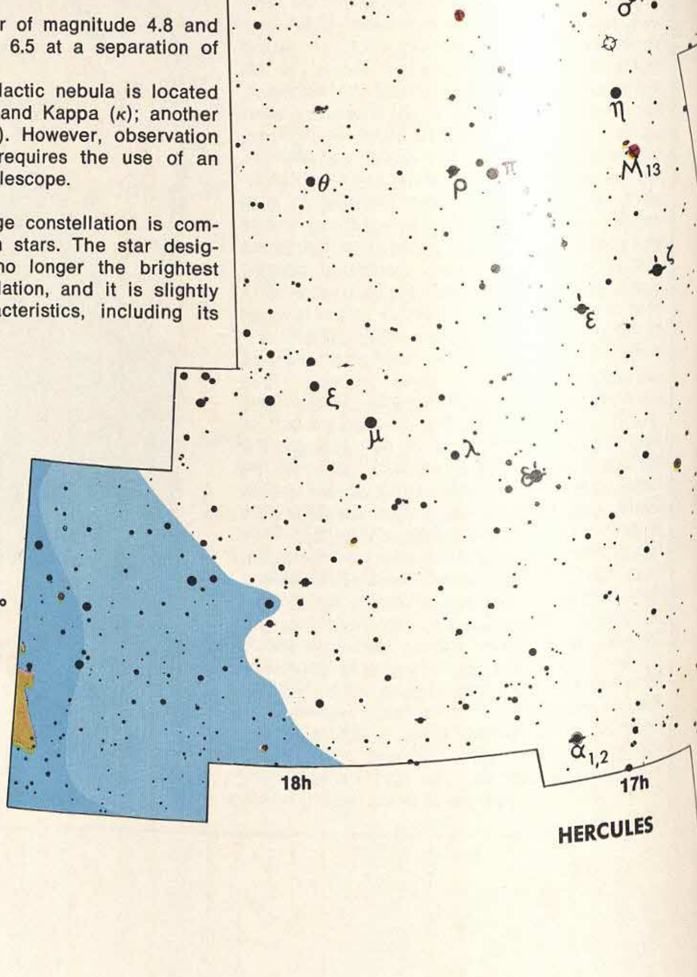
DRACO—Draco, the Dragon, covers quite a large area of the sky, embracing the north pole and extending for 12 hours in right ascension; in declination it ranges from near the pole to almost +40°. Because it is circumpolar, the constellation is always above the horizon; it appears in one position at one time of the year, and at another time of the year it appears upside down. During July, at the height of the summer, it is between the pole and the zenith; in winter it is between the pole and the horizon. Because of its size and its position in the sky, it includes both an area of the Milky Way where the stars are most dense and an area of sky far from the Milky Way where several extragalactic nebulas are to be seen.

None of the stars of Draco is markedly bright; the characteristic zigzag alignment of the main stars is apparent only on an extremely clear night. All the other stars are quite dim and barely visible to the naked eye, and only a few double stars are of interest. At least 60 double stars are within reach of small telescopes, although some are difficult to observe. Eta (η) is made up of a star of magnitude 8.1 beside a main star of magnitude 2.1, with a distance between the two of 4.7″. Mu (μ) comprises two stars of about the 5th magnitude 3.2″ apart. Nu (ν), whose two components are of magnitude 4.6 at a distance of 62″, is easily within reach of any instrument having a magnification of 20 X.

Other doubles are found among the brighter stars of Draco, but some weaker ones, which must be viewed through a strong telescope, are also of interest. For example Phi (ϕ) is composed of one star of magnitude 4.8 and another of magnitude 6.5 at a separation of only 0.5″.

A beautiful extragalactic nebula is located between Lambda (λ) and Kappa (κ); another is found near Iota (ι). However, observation of these spectacles requires the use of an extremely powerful telescope.

HERCULES—This large constellation is composed entirely of dim stars. The star designated Alpha (α) is no longer the brightest object in the constellation, and it is slightly variable. Many characteristics, including its



reddish color, make it interesting. The star belongs to the class of red giants and has a diameter at least as large as that of the Earth's orbit. Moreover, it is a binary, with the primary star of the 3rd magnitude and the secondary star of the 5th. The distance between them, resolvable with the smallest telescopes, is 4.6″. About a hundred double stars are found in the constellation.

Hercules, lying beside the Milky Way, is endowed with a rich background of stars. It contains an enormous globular cluster known as M13. Even with the naked eye it can be found between Eta (η) and Xi (ξ); it is clearly visible on cloudless nights, appearing as a slightly blurred star. Through a telescope, an almost perfectly circular luminous spot is seen, fading away toward the dark of the sky without any distinct edge. With a telescope of at least 15 cm (about 6 in.), individual stars can be distinguished within this luminosity—the brightest stars of the cluster. With a telescope of 30 cm (about 12 in.) or more, thousands of stars can be counted. Although even the smallest photograph of the cluster would reveal many more stars than the most powerful telescope, the light from this object is so intense that direct viewing far surpasses any photograph.

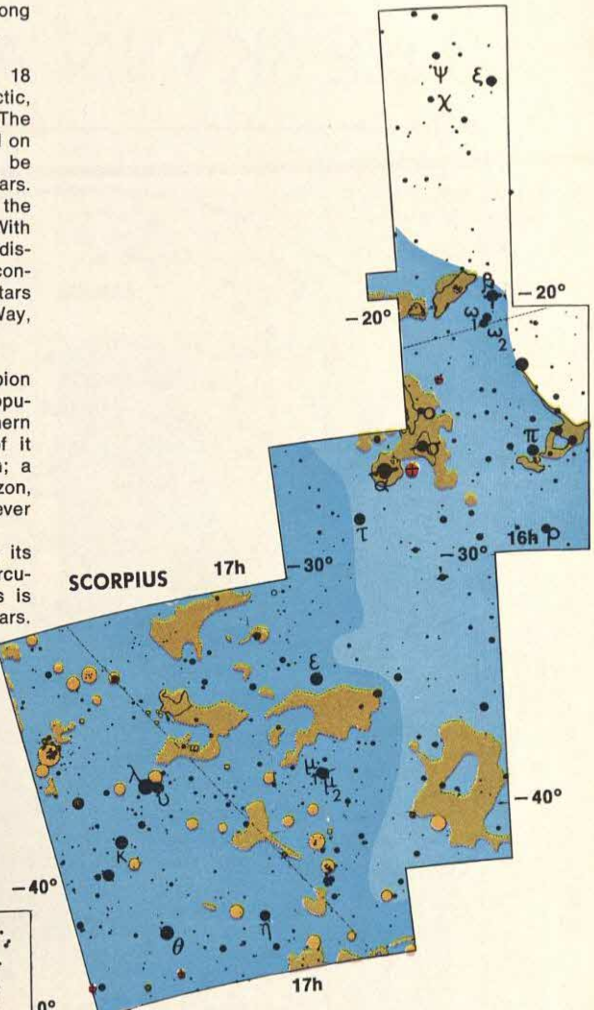
M13 contains more stars than any other cluster in the Northern Hemisphere. In the Southern Hemisphere is a cluster—ω Centauri—even brighter and denser with stars.

Another curiosity is the star designated Pi (π). It is toward this star that the sun is moving, carrying its system of planets with it. After some millions of years the sun, the Earth, and the other planets will be among the stars shining in that corner of the sky.

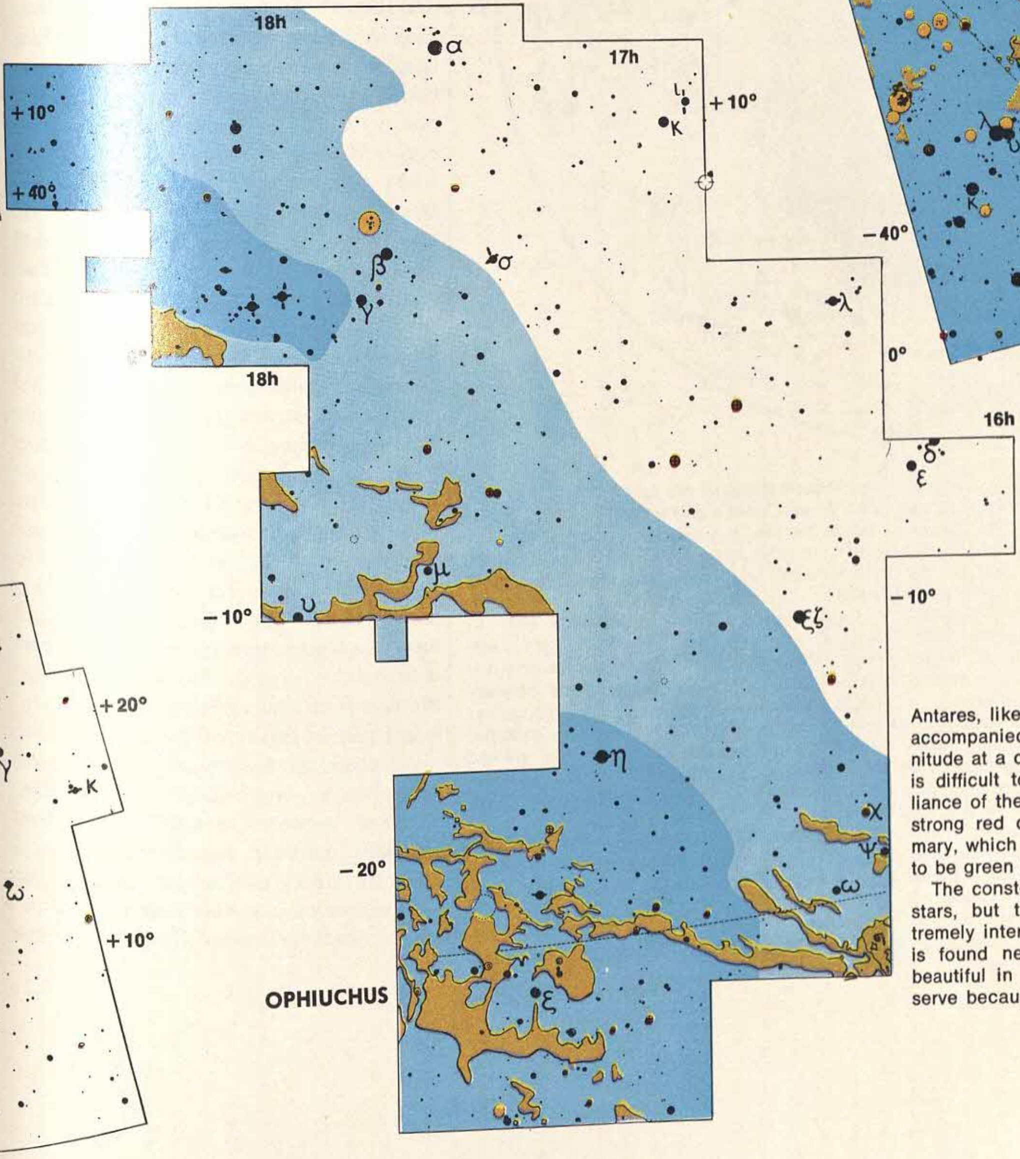
OPHIUCHUS—Ophiuchus contains about 18 star clusters, of which five are also galactic, and almost as many planetary nebulas. The positions of the main clusters are indicated on the map, and the brightest of them can be observed with a small telescope or binoculars. In the largest of the galactic clusters, the brightest stars are readily distinguished. With a small telescope, about 60 stars can be discerned as doubles. Many areas of this constellation are densely populated with stars belonging to the background of the Milky Way, which runs through the constellation.

SCORPIUS—The constellation of the Scorpion is among the most beautiful and densely populated in the sky. It lies entirely in the Southern Hemisphere, and only a small portion of it appears high above the northern horizon; a larger portion lies quite low on the horizon, and the greatest part of the constellation never appears at all in the Northern Hemisphere.

The first marvel of the constellation is its principal star, Antares, which is, like α Herculis, a red giant. The diameter of Antares is greater than the diameter of the orbit of Mars.



SCORPIUS



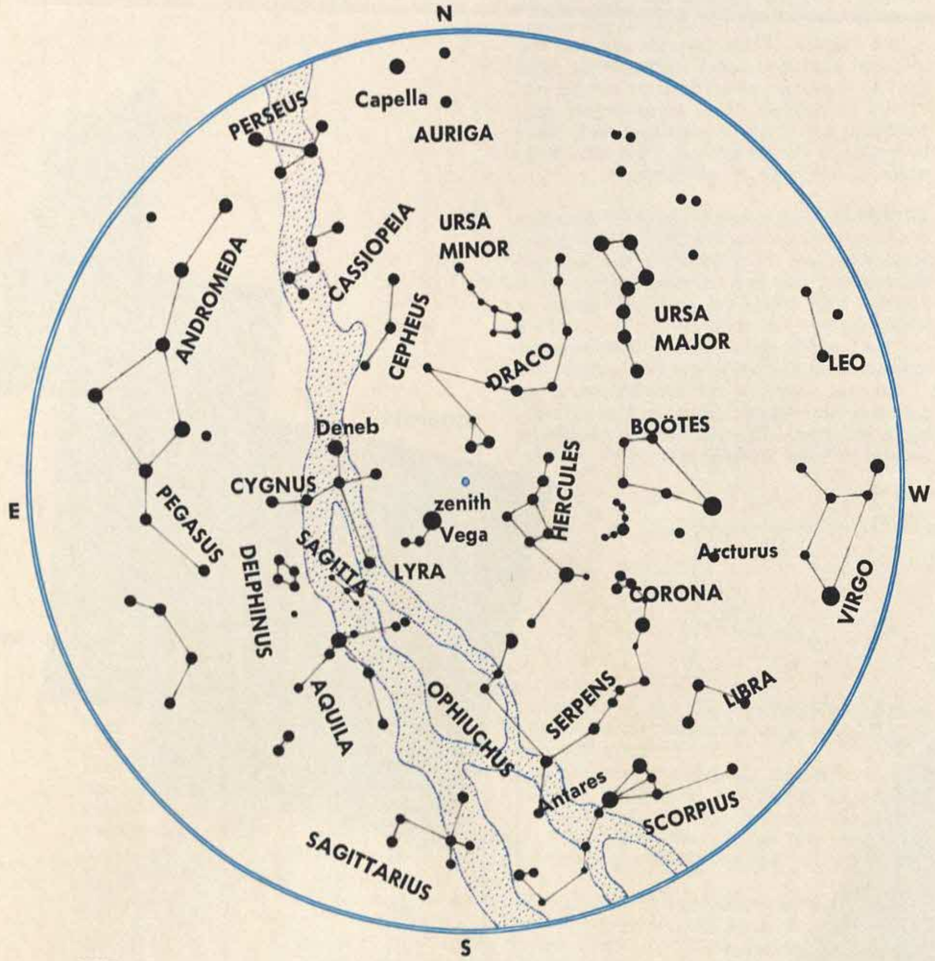
OPHIUCHUS

Antares, like α Herculis, is a binary star. It is accompanied by a star of about the 5th magnitude at a distance of 3″. The secondary star is difficult to see because of the great brilliance of the primary star and because of the strong red coloration of the light of the primary, which makes the secondary star appear to be green (no star is naturally green).

The constellation contains few other double stars, but the 24 galactic clusters are extremely interesting. The largest cluster, which is found near Antares, is among the most beautiful in the sky, but it is difficult to observe because it is so low on the horizon.

THE SKY IN AUGUST

Sagittarius, Scutum, Sagitta, Aquila, Vulpecula, and Lyra



THE AUGUST SKY—During August, Deneb, the principal star of the constellation Cygnus (the Swan), shines near the zenith. Below Deneb and to the west—but still high on the horizon—is Vega, the principal star in the constellation Lyra (the Lyre). At this time, it is the most brilliant star in the sky, but occasionally the planets Venus, Mars, and Jupiter may shine more brightly. Arcturus, in the constellation Boötes (the Herdsman), is setting in the west; Antares is in the southwest.

The alignment of these stars is helpful for finding other constellations. To the east, Pegasus and Andromeda are already high on the horizon; Ursa Major and Cassiopeia are midway between the horizon and the zenith, the former in the northwest and the latter in the northeast. Capella in the constellation Auriga (the Charioteer)—the highest of the stars in the winter group of constellations—is low on the horizon in the north, indicating that the winter constellations are far off below the horizon. When Capella and its winter cortege rise high in the sky, the weather will be quite cold. Stars are often associated with the weather of the seasons when they are most thoroughly visible in the sky.

Certain constellations are visible only in August, and then for but a few hours each night. These are stars that lie low on the horizon—such as those comprising the constellation Sagittarius (the Archer). This constellation has quite a low declination (the celestial equivalent of latitude) and must be viewed at the greatest height in its celestial journey, during the first few hours of the August evening.

Constellations that cross the meridian quite close to the horizon are observable for short periods only; they may be sought during the preceding months when they occur two hours earlier each month.

During the month of August, the sky is rich in beautiful constellations, and the Milky Way remains among the most spectacular sights. However, the high temperatures that characterize August may impede observation, and atmospheric dust may at times obscure the sky.

About August 10 or 11, the observer is provided with an outstanding treat, the Perseid meteor shower. This striking display occurs annually with great regularity and probably has been recurring for at least 40,000 years. The shower normally lasts for about five days, and it may be observed with the naked eye.

The meteors appear to come from a region in the sky in the vicinity of the constellation Perseus—hence the designation Perseid shower or Perseids. The point from which the meteors seem to radiate is called the radiant point or position; in this case, the approximate radiant position is right ascension 3 hrs and declination +58°.

On a clear night during the height of the Perseid shower, a patient observer may see the trails of about 50 or 60 meteors every hour. A pair of binoculars or a telescope can be used to extend the range of visual observations from the limit of the naked eye, which is about 5th or 6th magnitude, to the 12th or 13th magnitude. Binoculars with wide-angle lenses are especially helpful because they provide a broad field of view.

Probably the best way to carry on these observations is to watch a particular sector of the sky. For casual observations, the viewer does not need to locate the coordinates of the radiant position precisely, as long as the constellation Perseus is above the horizon. If Perseus is visible, meteors from that radiant may be seen in every part of the sky.

An observer may try to count the meteors he sees or he may try to plot the paths of meteors through the sky. For this latter activity, the observer needs a star chart and a good clock. He may plot the path of each meteor among the stars on the chart and record the time, the apparent magnitude or brightness of the meteor, and its color.

Groups of observers may work together, each person watching a different sector of the sky. Some observers find it helpful to have assistants to help with the plotting and recording operations; during meteor showers, more sightings may be made than can be recorded accurately by a single observer.

If two observers, located about 64 km (about 40 mi) apart, plot the same meteor, its height and radiant position can be roughly calculated. Professional astronomers (and some highly competent amateurs) make much more accurate measurements by using photographic and radio techniques. Nevertheless, the careful visual observer can play an important role in the study of meteors, especially in determining meteor rates and in supplying corrections for instrumental observations.

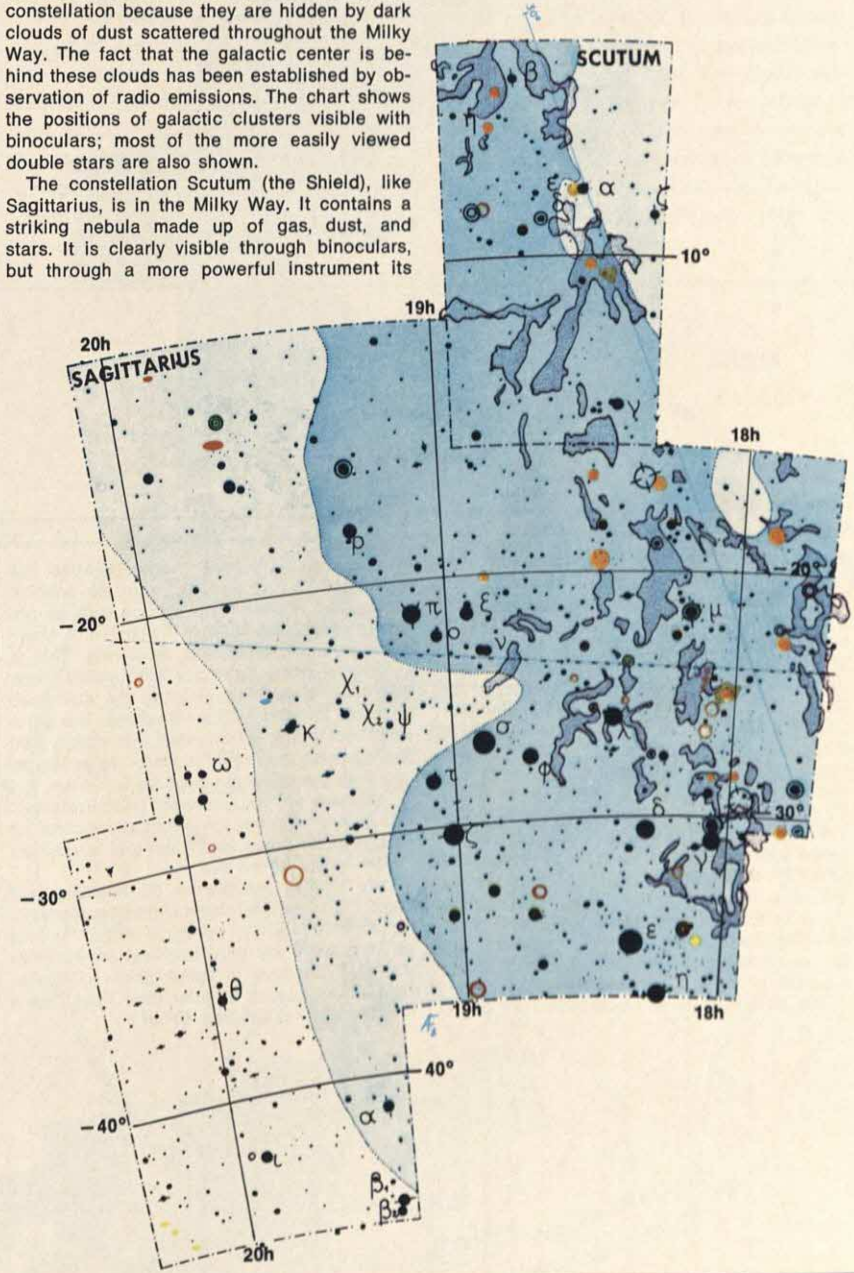
To improve the plotting accuracy of the visual observer, several aids have been developed. They include wire graticules, which are scales on transparent material in the focal plane of an optical instrument to help locate and measure objects. Another aid provides for the meteor path to be viewed not directly but in a rocking mirror that appears to put in the meteor path a number of kinks from which the meteor velocity may be deduced.

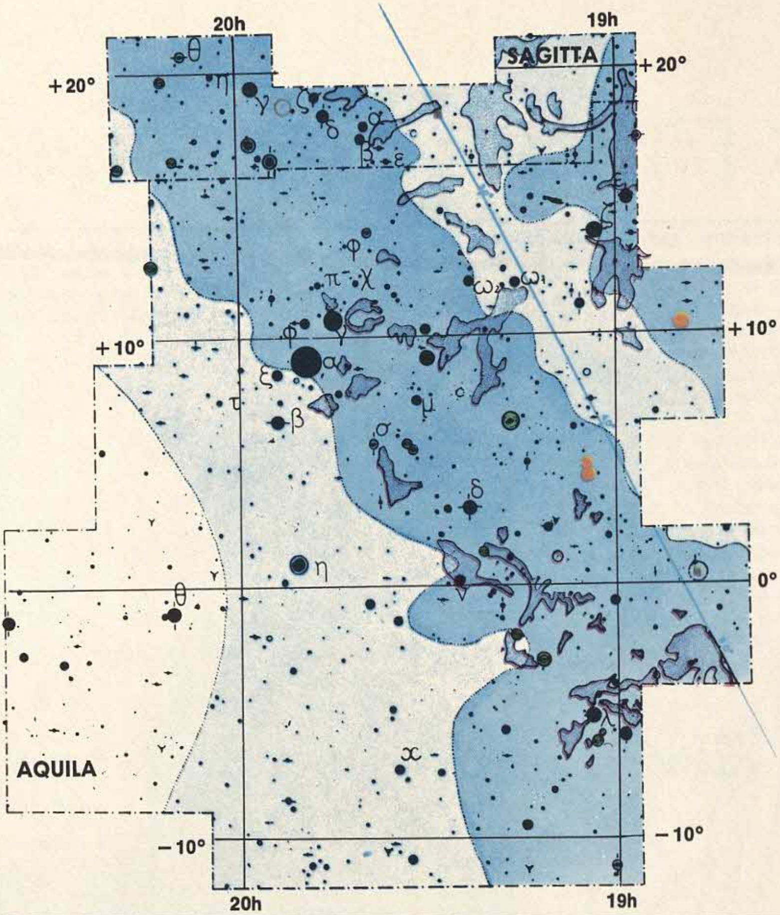
Because of the Earth's motion, about three to five times as many meteors may be seen each hour during the second half of a typical night as may be observed during the first half of the night. Therefore, the best observations are made between midnight and dawn.

Of course, meteors may be seen on practically any clear night of the year, but showers such as the Perseids provide excellent opportunities for sky observers to view these "visitors from outer space." Moreover, the warm nights of August provide the observer with a measure of comfort that he may not enjoy while observing a meteor shower in winter.

SAGITTARIUS AND SCUTUM—The constellation Sagittarius is found in the Milky Way, which is rich in faint stars; seen on a clear night, Sagittarius displays an incredible multitude of stars. The center of the Galaxy is in the direction of Sagittarius, but the stars of the galactic center cannot be seen through the constellation because they are hidden by dark clouds of dust scattered throughout the Milky Way. The fact that the galactic center is behind these clouds has been established by observation of radio emissions. The chart shows the positions of galactic clusters visible with binoculars; most of the more easily viewed double stars are also shown.

The constellation Scutum (the Shield), like Sagittarius, is in the Milky Way. It contains a striking nebula made up of gas, dust, and stars. It is clearly visible through binoculars, but through a more powerful instrument its appearance is truly spectacular. Moving the same telescope at random across the region will reveal a myriad of stars, indicating the enormous number of stellar objects that comprise the Milky Way.





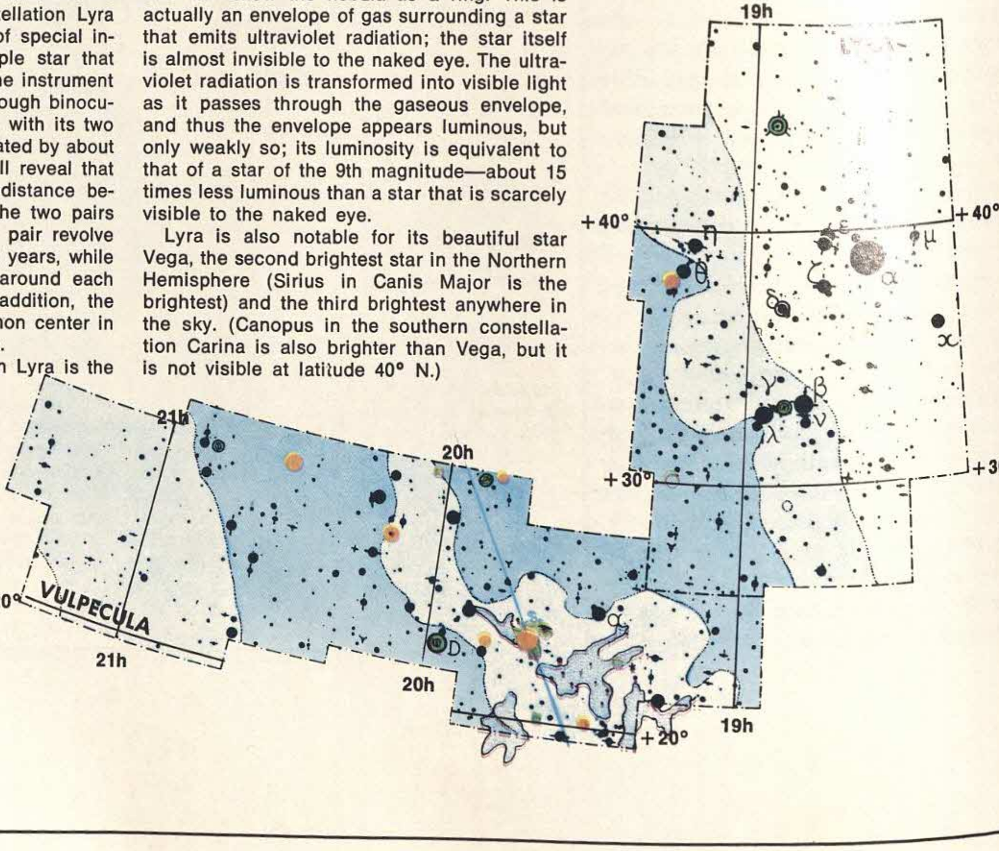
SAGITTA AND AQUILA—Sagitta (the Arrow) is the smallest constellation in the sky; it is composed of a few stars in the shape of an arrowhead. Some of its double stars may be observed.

Aquila (the Eagle) is found in the Milky Way. Above Gamma (γ), the star above and to the right of Altair (α), a beautiful cloud can be seen. The stars in the constellation Aquila are relatively sparse compared with the concentrations found in the regions immediately to the east and west. Here the Milky Way appears to divide, and the constellation is crossed by a bright branch to the east and another branch, less bright, to the west. This division of the galactic band is caused by the presence of interstellar dust along the galactic plane.

VULPECULA AND LYRA—Vulpecula (the Fox) is also part of the Milky Way. The most interesting object in the constellation that is visible with a small telescope is the so-called Dumbbell Nebula; its position is indicated on the chart by the letter D. The constellation Lyra (the Lyre) contains two objects of special interest. One is Epsilon (ε), multiple star that provides a test of the power of the instrument through which it is observed. Through binoculars, it appears as a double star, with its two principal components being separated by about 3′; a more powerful telescope will reveal that the star is quadruple, with the distance between the two stars in each of the two pairs about 2″ to 3″. The stars in one pair revolve around each other in about 2,000 years, while those in the other pair revolve around each other in about 4,000 years; in addition, the two pairs revolve around a common center in a period of about a million years.

The second important object in Lyra is the planetary Ring Nebula, found between the stars Beta (β) and Gamma (γ) in the position shown on the chart. A telescope with an objective of at least 100-mm (about 4-in.) diameter will show the nebula as a ring. This is actually an envelope of gas surrounding a star that emits ultraviolet radiation; the star itself is almost invisible to the naked eye. The ultraviolet radiation is transformed into visible light as it passes through the gaseous envelope, and thus the envelope appears luminous, but only weakly so; its luminosity is equivalent to that of a star of the 9th magnitude—about 15 times less luminous than a star that is scarcely visible to the naked eye.

Lyra is also notable for its beautiful star Vega, the second brightest star in the Northern Hemisphere (Sirius in Canis Major is the brightest) and the third brightest anywhere in the sky. (Canopus in the southern constellation Carina is also brighter than Vega, but it is not visible at latitude 40° N.)



THE SKY IN SEPTEMBER

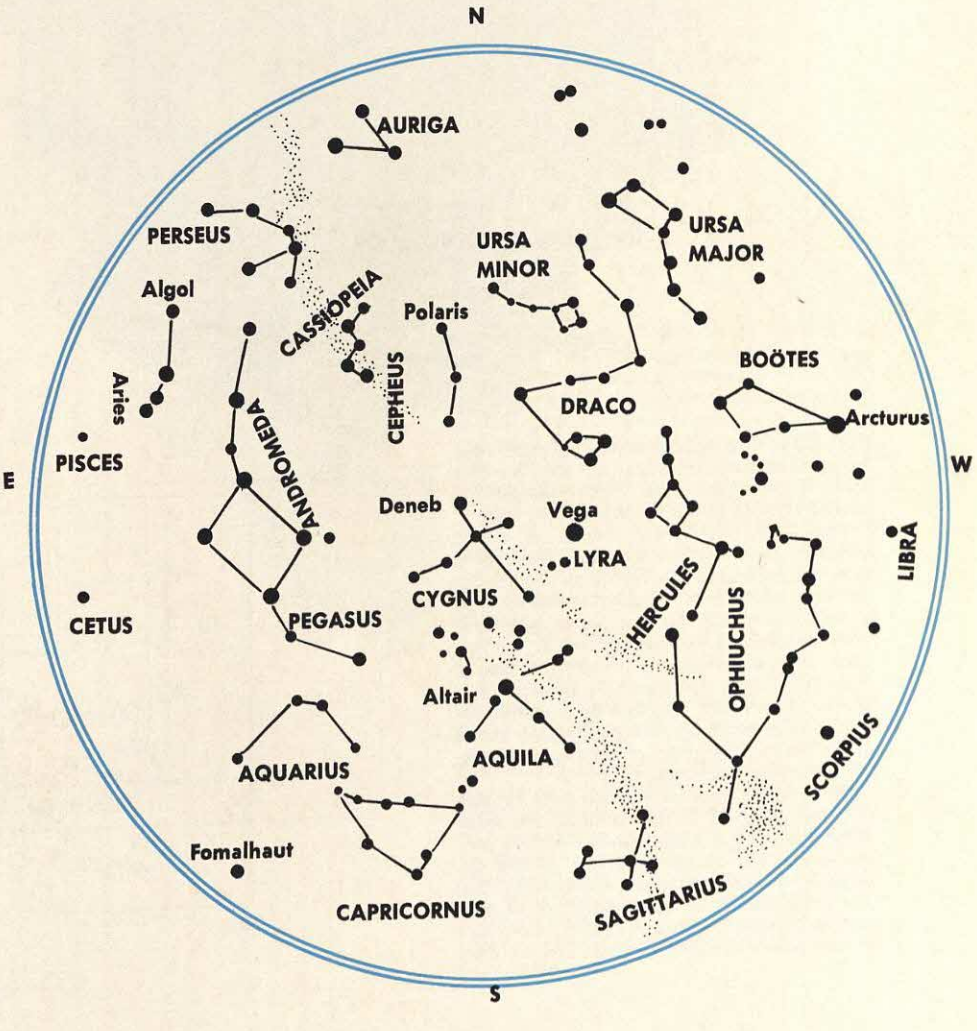
Cepheus, Capricornus, Cygnus, Delphinus, and Equuleus

The mild evenings of September mark the end of the summer season and provide especially favorable conditions for astronomical observations. The end of the hot season is often marked by storms, which clear the atmosphere of the dust that frequently obscures the sky during July and August. The nights in September are often intensely starry, and through a telescope an observer can pick out nebulas and other celestial objects of low brilliance.

On nights immediately following a storm, the observer is well advised to observe the sky with the naked eye only; telescopic images may appear distorted and confused because of continuing atmospheric disturbance. On subsequent nights, however, as the atmosphere becomes calmer, sightings through the still air may be quite sharp indeed.

The revolution of the Earth produces a continuous passage of the constellations; some stars visible in August have sunk beneath the horizon, while others have risen in the sky. The chart shows those constellations that are in the most favorable viewing positions during the month of September.

Inasmuch as many constellations bear the names of figures in ancient Greek myths, the sky watcher may enhance his enjoyment by becoming acquainted with mythology. For example, Cepheus was the mythological king of Ethiopia, the husband of vain Cassiopeia, and the father of Andromeda. According to one story, the god Poseidon, to punish Cassiopeia, commanded that she chain Andromeda to a rock near the sea; there, a great sea monster (Cetus) was to devour the young princess. However, Perseus happened by and rescued her. In some versions of the story, Perseus rode the winged horse, Pegasus.

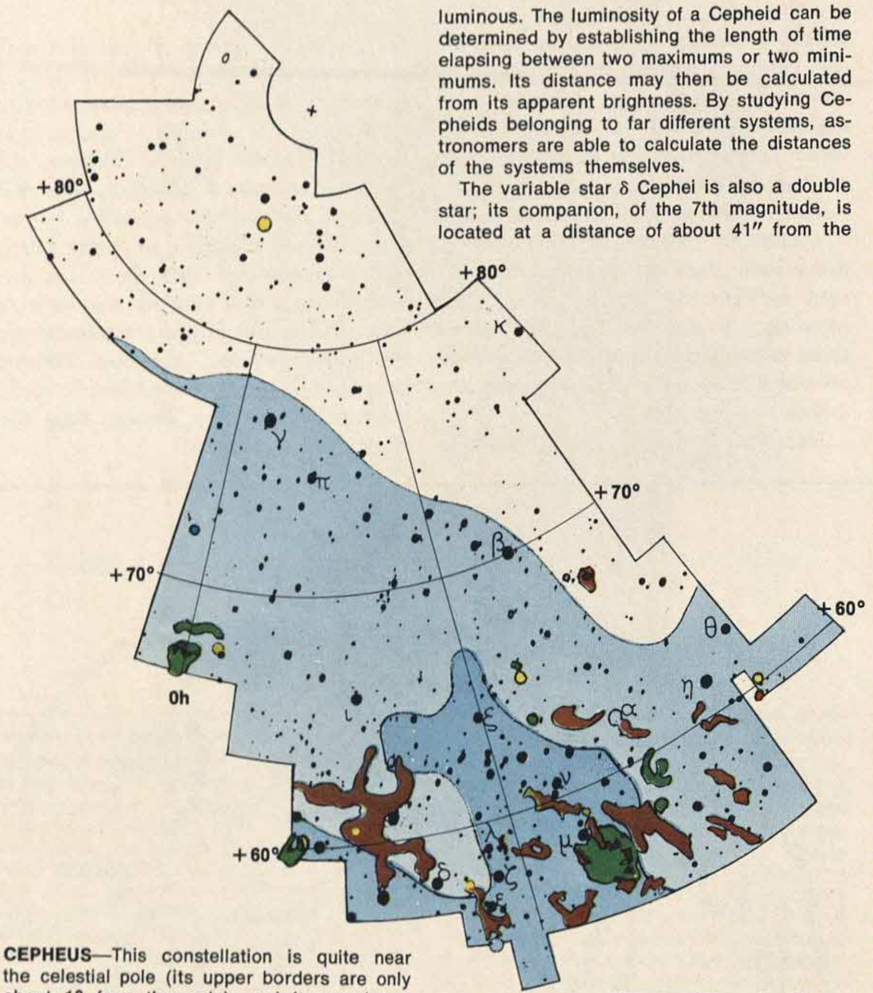


THE SEPTEMBER SKY—This chart shows the positions of the constellations at ten o'clock, solar time, on a September evening. Boötes (the Herdsman), Ursa Major (the Great Bear), and Auriga (the Charioteer) are too low on the horizon to be observed clearly, as are Ophiuchus (the Serpent-Bearer), Eridanus (the River), and Draco (the Dragon). Cygnus (the Swan), Aquila (the Eagle), and other summer constellations are in favorable positions for observation, but only Cygnus may be easily observed.

In the east are constellations that, although initially low on the horizon, continue to rise during the night. Among them are Pegasus, Pisces (the Fishes), Aries (the Ram), Cetus (the Whale), Andromeda, and Perseus. Taurus (the Bull), which is best observed during the late autumn and winter, is beginning to appear on the eastern horizon. In the most favorable positions for observation are the constellations on the southern horizon: Piscis Austrinus (the Southern Fish), Capricornus (the Sea Goat), Aquarius (the Water Carrier), and Cepheus. At the hour shown on the chart, the brightest star near the zenith is Deneb in the constellation Cygnus.

September is still a favorable month for observing the Milky Way, which passes nearly through the zenith, cutting the horizon in a circle from northeast to southwest.

The constellations shown high on the chart are those at their greatest altitude in September—that is, those that pass at the greatest height above the southern horizon. Those crossing high on the meridian—Cygnus, for example—can be seen during other months as well; however, some constellations, such as Piscis Austrinus, can be observed only for a short time.



CEPHEUS—This constellation is quite near the celestial pole (its upper borders are only about 1° from the pole), and it contains a classic variable star and some double stars.

The classic variable star is Delta (δ), which, although fairly bright, does not maintain a constant brightness; its variations in light occur with chronometric regularity according to a precise law. This star ranges in brightness from magnitude 3.6 to magnitude 4.2. The variation is characterized by a rapid increase in luminosity from a minimum to a maximum in a period of 38 hours, followed by a slower decrease from maximum to minimum in a period of 91 hours. The rates of increase and decrease are strictly linear.

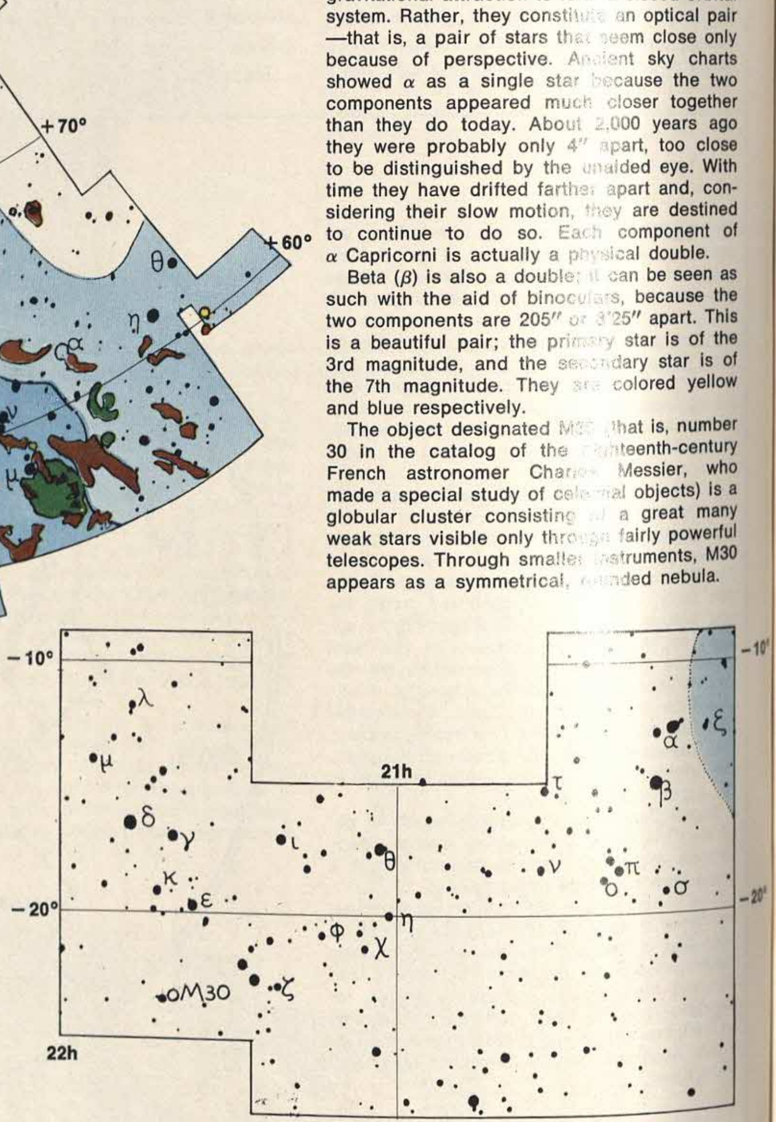
The star δ Cephei is not the only variable star that behaves in this manner; the many other stars of this type, found in various constellations, are called Cepheids. All the Cepheids have characteristic luminosities that are proportionate to the logarithms of their periods of variation; those requiring more time to complete a cycle of variation are the more luminous. The luminosity of a Cepheid can be determined by establishing the length of time elapsing between two maximums or two minimums. Its distance may then be calculated from its apparent brightness. By studying Cepheids belonging to far different systems, astronomers are able to calculate the distances of the systems themselves.

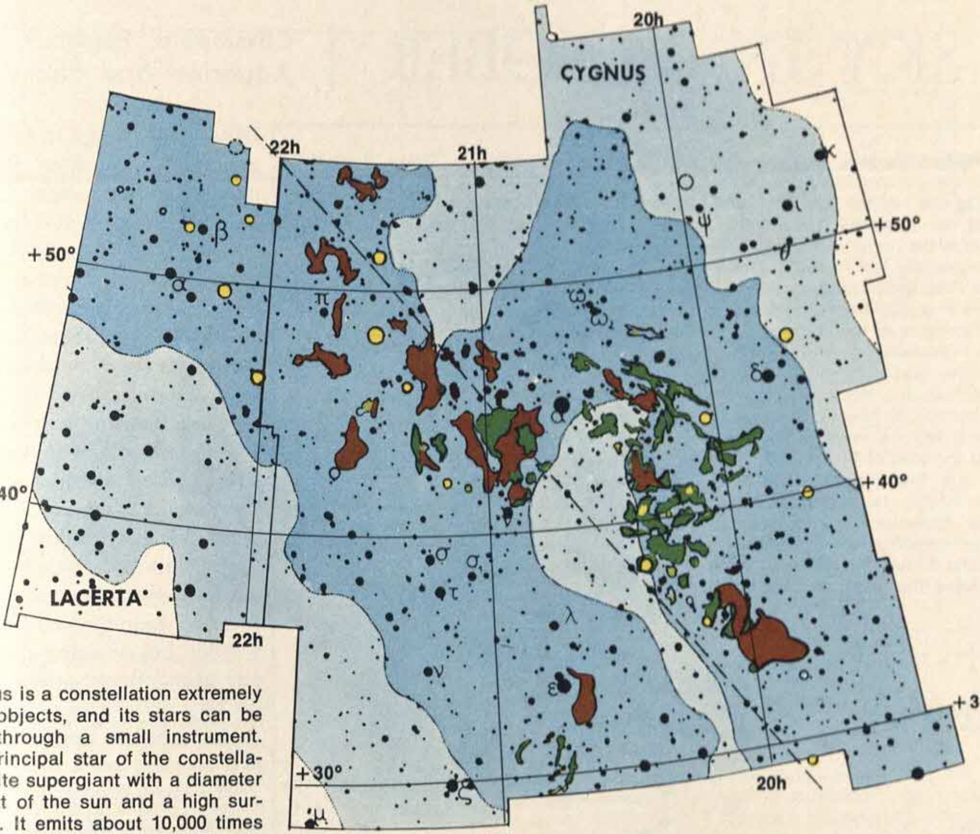
The variable star δ Cephei is also a double star; its companion, of the 7th magnitude, is located at a distance of about 41″ from the primary star. Double stars are pairs of stars linked by gravitational attraction, as the planets are linked to the sun. The reciprocal position of the stars varies as the stars revolve—in elliptical orbits—around a common center of gravity. Periods of revolution may vary from a few days to thousands of years. Other double stars shown on this chart are Beta (β), Chi (χ), and Xi (ξ); β Cephei is also a Cepheid variable.

CAPRICORNUS — Although this constellation lies alongside a branch of the Milky Way, it is not particularly dense with stars. Its principal star (α) appears to the naked eye to be a double star or binary, but the two stars comprising it are 6′15″ apart and they are not linked by gravitational attraction to form a closed orbital system. Rather, they constitute an optical pair —that is, a pair of stars that seem close only because of perspective. Ancient sky charts showed α as a single star because the two components appeared much closer together than they do today. About 2,000 years ago they were probably only 4″ apart, too close to be distinguished by the unaided eye. With time they have drifted farther apart and, considering their slow motion, they are destined to continue to do so. Each component of α Capricorni is actually a physical double.

Beta (β) is also a double; it can be seen as such with the aid of binoculars, because the two components are 205″ or 3′25″ apart. This is a beautiful pair; the primary star is of the 3rd magnitude, and the secondary star is of the 7th magnitude. They are colored yellow and blue respectively.

The object designated M30 (that is, number 30 in the catalog of the eighteenth-century French astronomer Charles Messier, who made a special study of celestial objects) is a globular cluster consisting of a great many weak stars visible only through fairly powerful telescopes. Through smaller instruments, M30 appears as a symmetrical, rounded nebula.



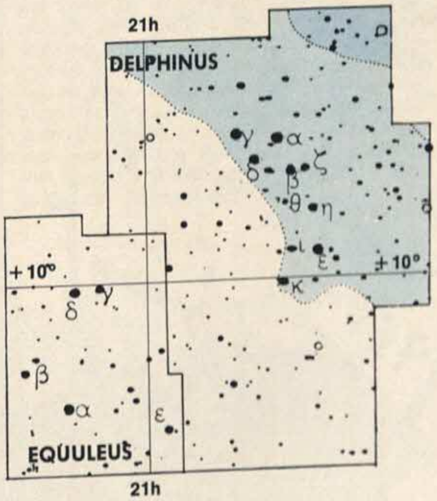


CYGNUS—Cygnus is a constellation extremely rich in celestial objects, and its stars can be observed even through a small instrument. Deneb (α), the principal star of the constellation, is a blue-white supergiant with a diameter several times that of the sun and a high surface temperature. It emits about 10,000 times as much light as the sun; in fact, if Deneb were in the place of the sun, the Earth would be quickly incinerated.

A telescope trained anywhere between Deneb and Albireo (β)—the star at the opposite end of the cross formed by the principal stars of Cygnus—will have its field filled with stars of the Milky Way, which is densely populated in this region. In the middle latitudes the stars of Cygnus and those of the Milky Way (where it passes through Cygnus) appear quite high in the sky; therefore, their light is subject to a minimum of atmospheric absorption.

The marvel of the constellation is the beautiful Albireo, a double star with brilliantly colored components. The 3rd-magnitude primary star has a gorgeous golden-yellow color, and its companion, with magnitude 5.3, has an intense blue color. The two stars are separated by about 34.6″ of arc. The nearness of the stars makes the color contrast seem even greater. Observation of the spectacle requires a telescope with an objective of at least a 50-mm (about 2-in.) diameter.

Another object worthy of attention is Chi (χ), which varies irregularly in brightness, decreasing from a magnitude of about 4.5 to a magnitude of about 14, and which returns to its former brightness in about 409 days. Sometimes this variable star can be seen clearly, but at other times it can be seen only through a telescope having an objective of at least 40 cm (about 16 in.).



The double star designated 61 Cygni is not shown on this chart because it changes position rapidly, moving across the sky through an arc of about 5″ each year. This large proper motion led astronomers to assume that the star is quite close to the solar system. In 1838, however, the German astronomer Friedrich Wilhelm Bessel established its distance at about 11 light-years—that is, its light, traveling at the speed of 300,000 km/sec (186,000 mi/sec), takes 11 years to reach the Earth. This marked the first time that the distance of a star was established through measurements of stellar parallax.

Many other double stars and beautiful nebulas in Cygnus appear on the chart.

Beside Cygnus is a small constellation, Lacerta (the Lizard), which, because it is close to the Milky Way, contains rich open clusters.

DELPHINUS AND EQUULEUS—Delphinus (the Dolphin or Job's Coffin) contains enough bright stars to give this constellation its characteristic design. Through a small telescope, an observer can pick out a binary (γ) and a triple star worthy of observation. Equuleus (the Little Horse) is even smaller than Delphinus; it consists of rather faint stars, among which a wide double and a closely grouped triple stand out.

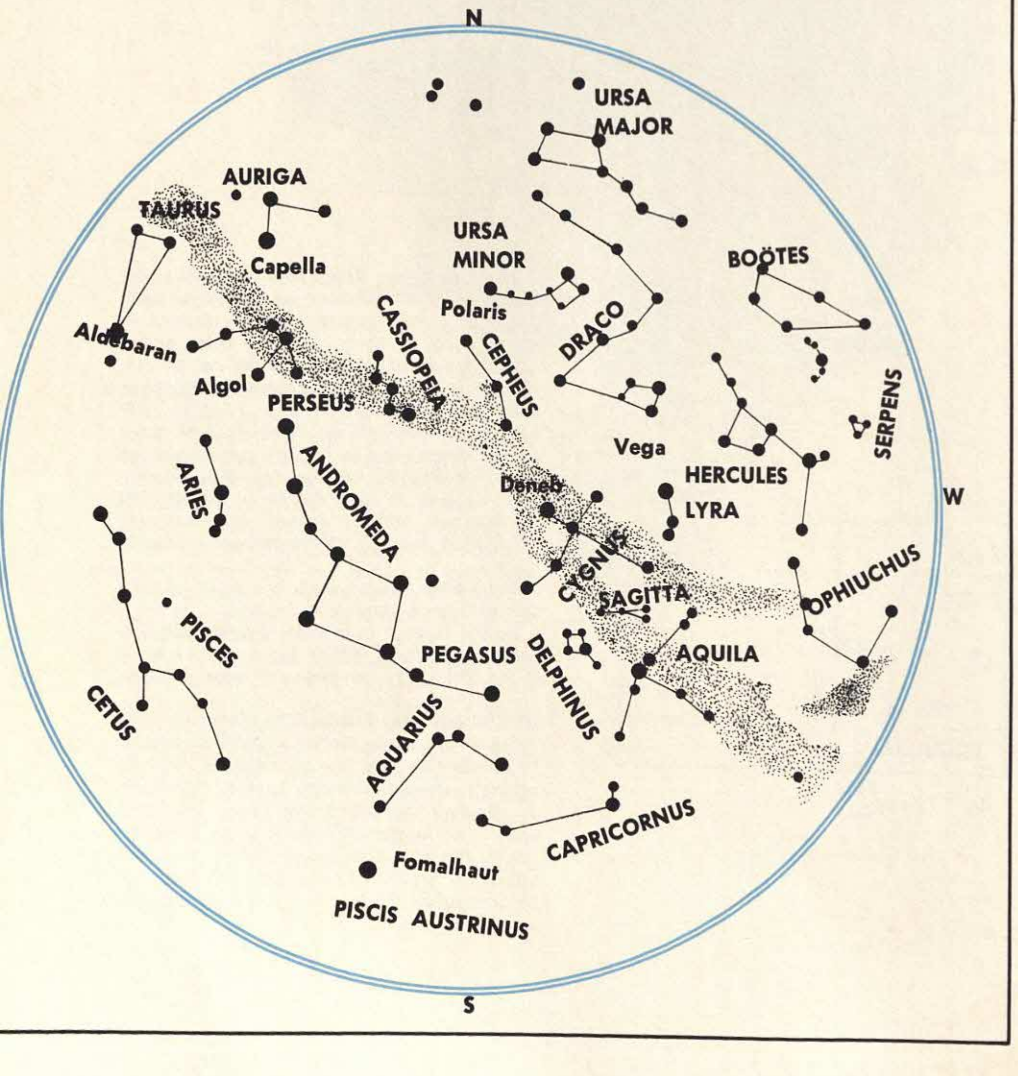
THE SKY IN OCTOBER | Cassiopeia, Pegasus, Aquarius, and Pisces

THE OCTOBER SKY—This star chart shows the disposition of the constellations in October with respect to the horizon and the four cardinal points of the compass. Ursa Major (the Great Bear) is in the north as always, but this month it is especially low in the sky between Polaris (the Pole Star) and the northern horizon. Across the Pole Star from Ursa Major, quite high on the horizon, is the constellation Cassiopeia. The constellation Auriga (the Charioteer) is in the northeast; its brightest star, Capella, which during the summer was quite low on the horizon, is now rising toward the zenith where it will be seen during the winter months. To the east of Auriga, still low on the horizon, are the Pleiades and the Hyades and the bright, 1st-magnitude star Aldebaran of the constellation Taurus (the Bull). Above these constellations is Perseus.

The constellations Cetus (the Whale), Pisces (the Fishes), Aries (the Ram), and Andromeda lie to the southeast. These constellations are better observed later in the night when the rotation of the sky has carried them higher in the sky than they are at nine o'clock in the evening.

In the west the constellations Draco (the Dragon), Lyra (the Lyre), Sagitta (the Arrow), and Delphinus (the Dolphin) are about to set; the constellation Cygnus (the Swan), on the other hand, is still well above the horizon and in a favorable position for observation. To observe Cygnus in October, the observer should not wait beyond 9:00 P.M. (10:00 P.M., where daylight saving time is in effect); later the constellation descends to the horizon and sinks beneath it.

On the meridian to the south, Pegasus, Aquarius (the Water Carrier), and Piscis Austrinus (the Southern Fish) are in excellent positions for observation.



Observing the sky in October is often a rewarding experience. Rainy days alternate with clear, serene nights; the summer haze is gone, and the sky appears in all its majestic splendor. During this month certain precautions must be taken for telescopic observation. If the telescope is kept indoors where the air is warm, it should be taken outdoors at least a half hour before it is used in order that it may cool to a uniform temperature. Only then will the mirror (if it is a reflecting telescope) reach its full resolving power. In the case of a refracting telescope, the warm air that it contained while it was in the house may deposit moisture on the lenses as the telescope cools. This problem may be remedied simply by waiting a while before using the instrument; in any event, the observer must wait until his own eyes become accustomed to the darkness before beginning to observe the sky.

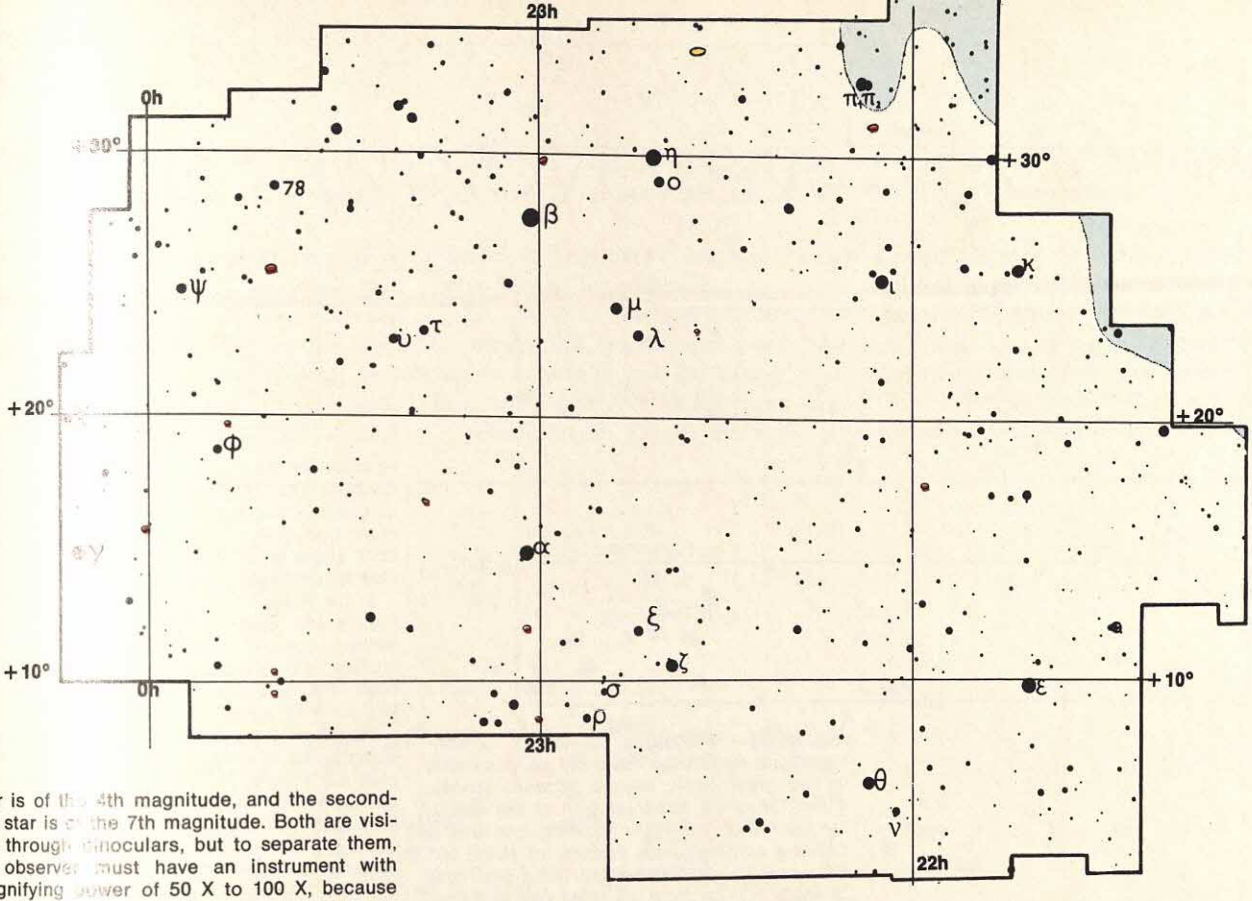
The sky in October is replete with interesting celestial objects but discussion here is limited to those new objects that are found near the meridian.

CASSIOPEIA — The constellation Cassiopeia extends from about 12° south of the north celestial pole to a little more than 45° south. It is easily distinguished by the characteristic W design formed by the alignment of its principal stars. Ancient observers imagined that in this design they saw Queen Cassiopeia—in Greek mythology, the wife of Cepheus and mother of Andromeda—seated on her throne. Because the design sometimes appears upside down (as a result of the rotation of the sky), the Arabs and some of the other ancient sky cartographers drew the figure of the queen tied to the throne so that she would not fall.

The central part of this large constellation extends over the branch of the Milky Way that passes near the north celestial pole; consequently, its stars appear in a region rich in stars, open clusters, and nebulas. Binoculars show an infinity of stars and star clusters in the area of this constellation; a more powerful instrument will show some nebulas as well, especially if low magnification is used.

The principal star of the constellation, Alpha (α), is a variable of the 2nd or 3rd magnitude. Gamma (γ) and Delta (δ) are also slightly variable. The observer may also see rather easily that α Cassiopeiae is a binary or double star; the primary, which can be seen with the naked eye, is reddish (although it is sometimes described as yellow), and its companion is a bluish star of the 9th magnitude. Such contrast in colors is one of the most striking properties of double and multiple stars.

The star Eta (η), also an interesting double, is perhaps the most beautiful in the constellation. Located between α and γ, it may be viewed with a small telescope. Both of its components are quite luminous; the primary



star is of the 4th magnitude, and the secondary star is of the 7th magnitude. Both are visible through binoculars, but to separate them, an observer must have an instrument with magnifying power of 50 X to 100 X, because the distance between the two components is about 9″ of arc.

Observation of the other double stars in this constellation requires the use of even more powerful instruments, and these doubles are too numerous to list here. On the other hand, observers will find it quite interesting to search for the open clusters with a telescope having a large objective and low magnification. About 20 open clusters may be found in the constellation Cassiopeia, mostly near the galactic equator (an imaginary line crossing the Milky Way in the region where it is brightest).

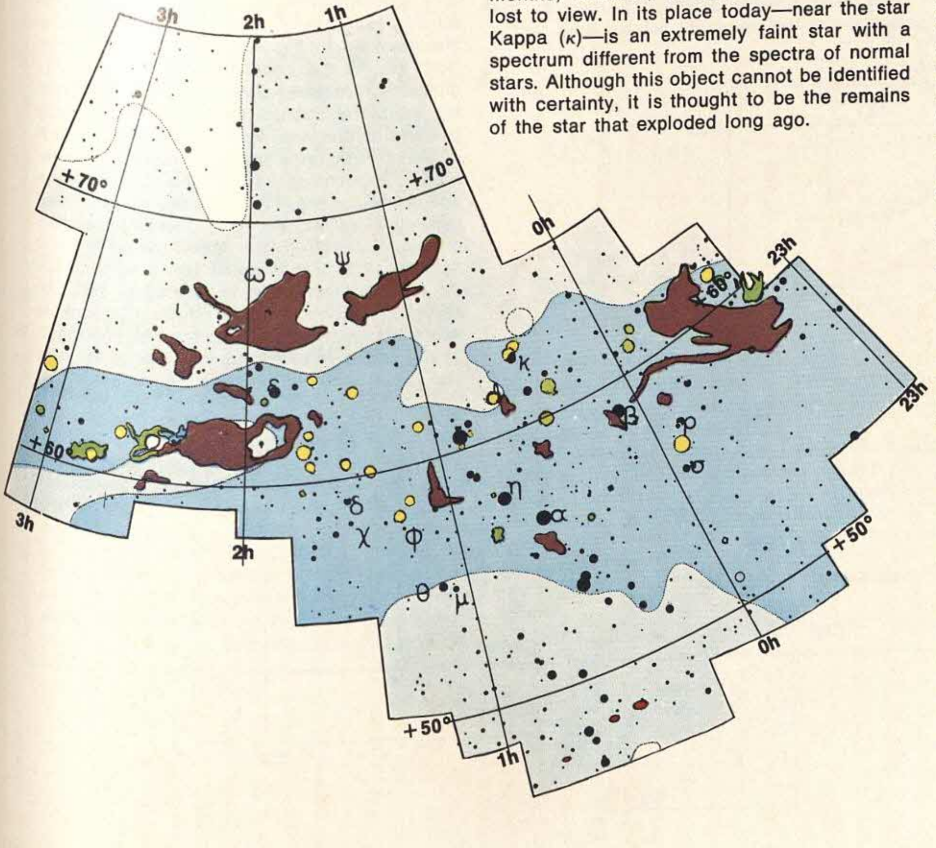
The most brilliant nova on record appeared in this constellation in 1572; because it was observed and described by Tycho Brahe, it has passed into history as Tycho's Nova. At the peak of its luminous splendor it supposedly shone brighter than the planet Venus and was visible during the day. After some months, however, its light dimmed and was lost to view. In its place today—near the star Kappa (κ)—is an extremely faint star with a spectrum different from the spectra of normal stars. Although this object cannot be identified with certainty, it is thought to be the remains of the star that exploded long ago.

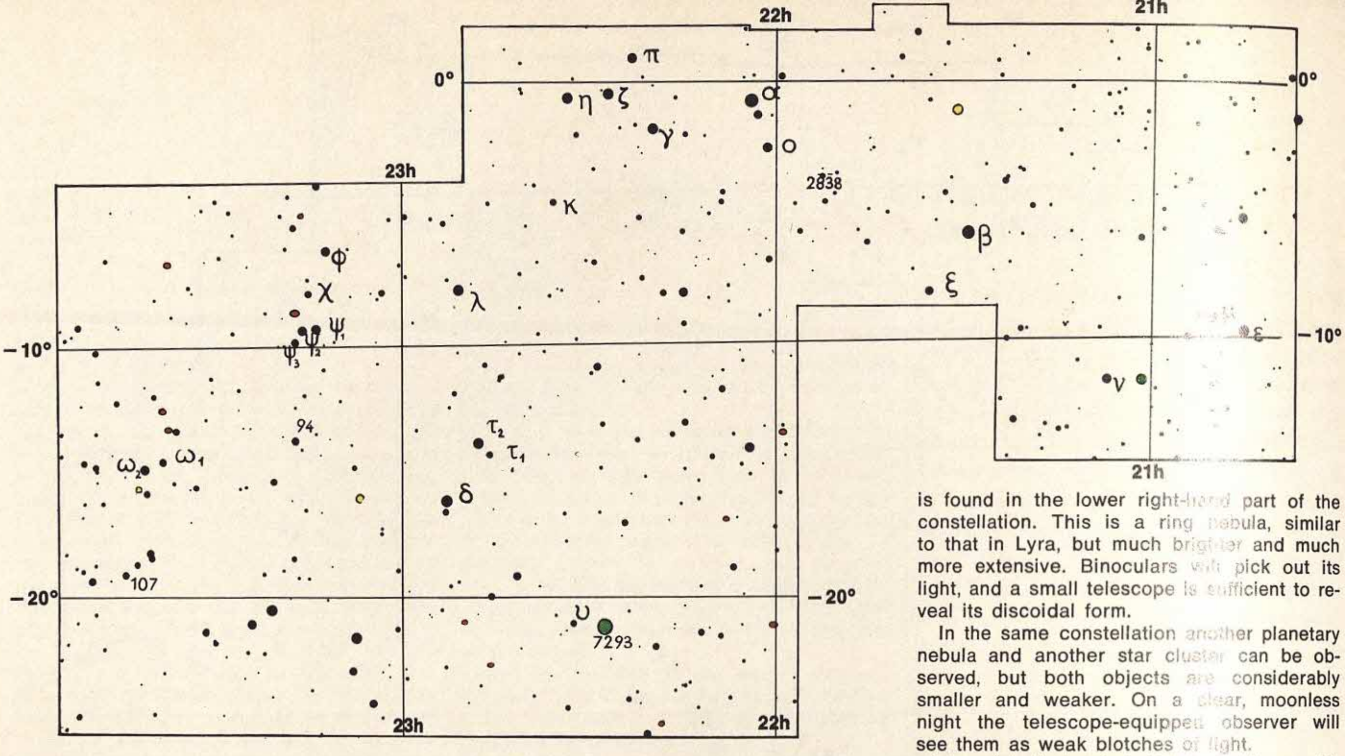
PEGASUS—Named for the winged horse of Greek mythology, the constellation Pegasus covers a considerable area of the sky, extending from east to west about 45° and from north to south about 34°. The stars Alpha (α), Beta (β), and Gamma (γ) are so disposed as to form, in conjunction with the star Alpheratz (α Andromedae) in the neighboring constellation, an almost perfect square. Pegasus is easily recognizable because of these stars.

Because Pegasus lies some distance from the Milky Way, it is poor in celestial objects that can be viewed with small telescopes; the only exceptions are a few double stars. No extragalactic nebulas in the constellation are bright enough to be seen, but a globular cluster and a faint planetary nebula may be found in the vicinity of the star Epsilon (ϵ). The globular cluster is clearly visible through a powerful telescope; its brightest stars, of the 15th magnitude, are invisible through a telescope of less than 30 cm (about 12 in.). Although double stars are rather abundant in this constellation, not all of them can be viewed with small telescopes.

One interesting double star is the one designated 78 on the chart. It consists of a primary star of the 5th magnitude and a secondary star of about the 8th magnitude. Both components are clearly visible through a small telescope, but the observer needs an instrument of high resolving power to see them separately, because the angular distance separating them is only 1.4″; only a telescope with a 15-cm (about 6-in.) objective will separate the two stars clearly, and then only if the optical quality of the objective is good.

One specially striking multiple (a triple star) is ϵ Pegasi, which is accompanied by two rather dim stars; whether or not their faint light can be seen depends on the diameter of the objective lens of the telescope. Near the primary star, which is of magnitude 2.5, are stars of magnitude 8.3 and magnitude 11.5; the former is located 140″ from the primary, while the latter is found 82″ from the primary.





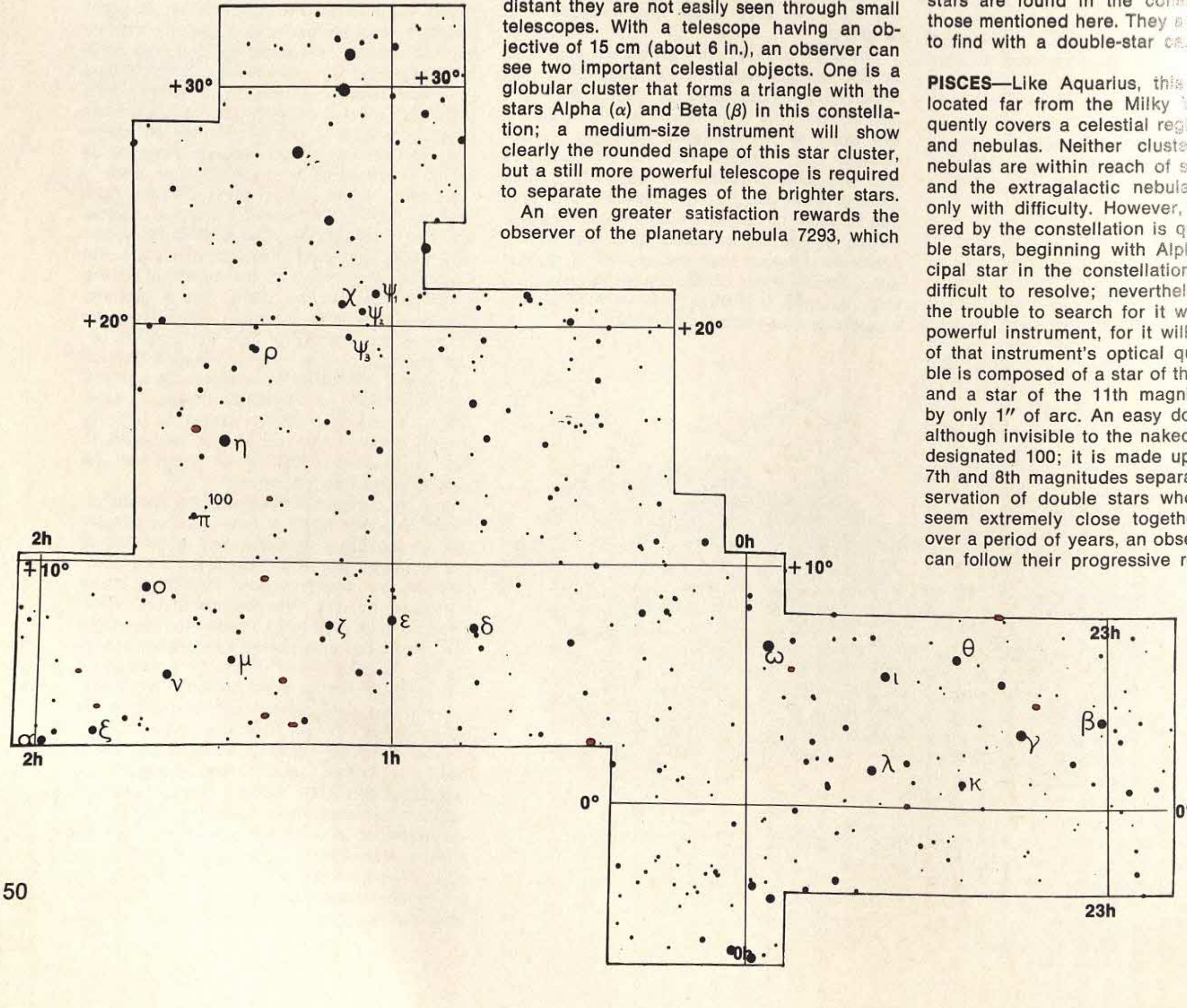
AQUARIUS—The zodiac consists of 12 constellations distributed along the ecliptic—that is, the great circle on the celestial sphere, which forms the apparent path of the sun in the course of the year. Aquarius, one of the zodiacal constellations, extends for about 50° from east to west and about 30° from north to south. It is far from the Milky Way and contains some extragalactic nebulas that are so distant they are not easily seen through small telescopes. With a telescope having an objective of 15 cm (about 6 in.), an observer can see two important celestial objects. One is a globular cluster that forms a triangle with the stars Alpha (α) and Beta (β) in this constellation; a medium-size instrument will show clearly the rounded shape of this star cluster, but a still more powerful telescope is required to separate the images of the brighter stars.

An even greater satisfaction rewards the observer of the planetary nebula 7293, which is found in the lower right-hand part of the constellation. This is a ring nebula, similar to that in Lyra, but much brighter and much more extensive. Binoculars will pick out its light, and a small telescope is sufficient to reveal its discoidal form.

In the same constellation another planetary nebula and another star cluster can be observed, but both objects are considerably smaller and weaker. On a clear, moonless night the telescope-equipped observer will see them as weak blotches of light.

The star designated 197 is a binary with components of magnitudes 5.0 and 6.5, situated 6.5″ apart. Omega (ω), with components of magnitudes 5.2 and 7.2, about 13.4″ apart, is another double in Aquarius. Finally, star number 2838 (in the Struve catalog) has components of magnitudes 6 and 6.8, separated by 21″. The primary star in 2838 is yellow, and the secondary is blue. Many other double stars are found in the constellation besides those mentioned here. They are relatively easy to find with a double-star catalog.

PISCES—Like Aquarius, this constellation is located far from the Milky Way and consequently covers a celestial region poor in stars and nebulas. Neither clusters nor galactic nebulas are within reach of small telescopes, and the extragalactic nebulas can be seen only with difficulty. However, the region covered by the constellation is quite rich in double stars, beginning with Alpha (α), the principal star in the constellation. The star α is difficult to resolve; nevertheless, it is worth the trouble to search for it with a sufficiently powerful instrument, for it will serve as a test of that instrument's optical quality. This double is composed of a star of the 4th magnitude and a star of the 11th magnitude, separated by only 1″ of arc. An easy double to resolve, although invisible to the naked eye, is the star designated 100; it is made up of stars of the 7th and 8th magnitudes separated by 16″. Observation of double stars whose components seem extremely close together is important; over a period of years, an observer quite likely can follow their progressive revolutions.



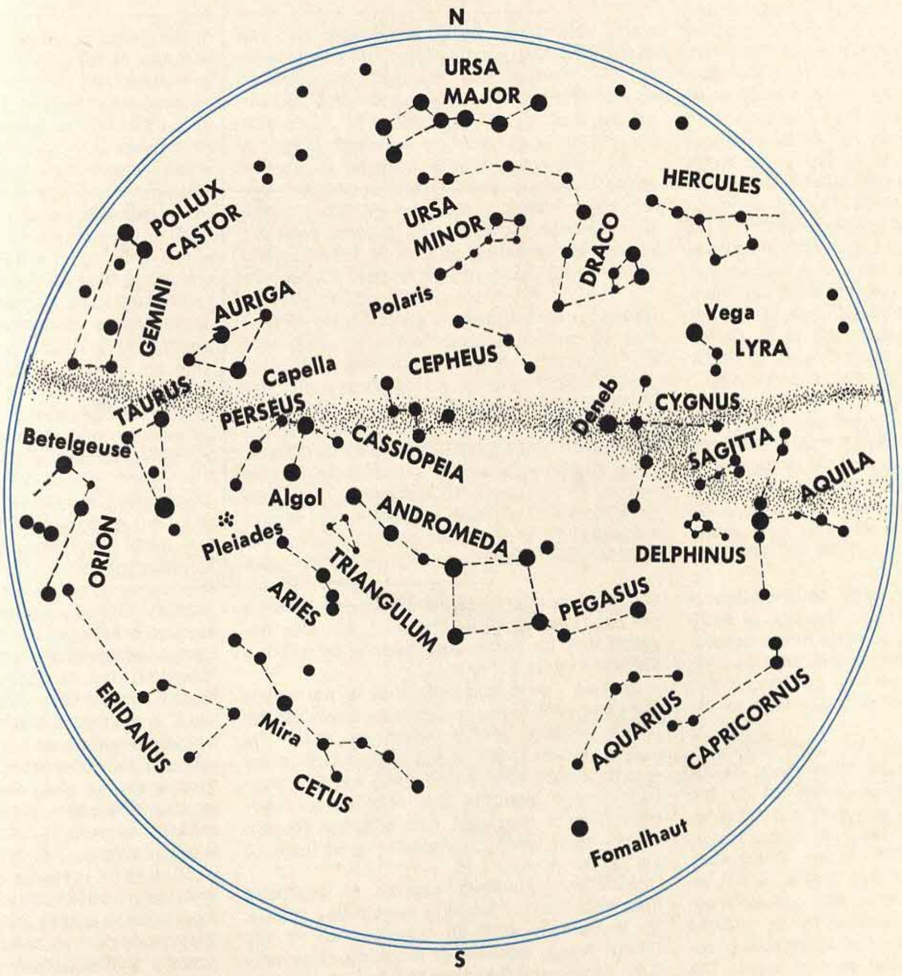
THE SKY IN NOVEMBER

Cetus, Aries, Andromeda, and Triangulum

In November the sky displays some spectacular constellations, rich in details that can be seen with the aid of small telescopes. Although the nights may be cold, the sky is usually clear and viewing conditions are generally excellent, even with refracting instruments. Many celestial objects of exceptional interest present themselves to the observer.

The famous Leonid meteor showers occur during this month every year; these showers normally last for about seven days, with November 16 the mean date.

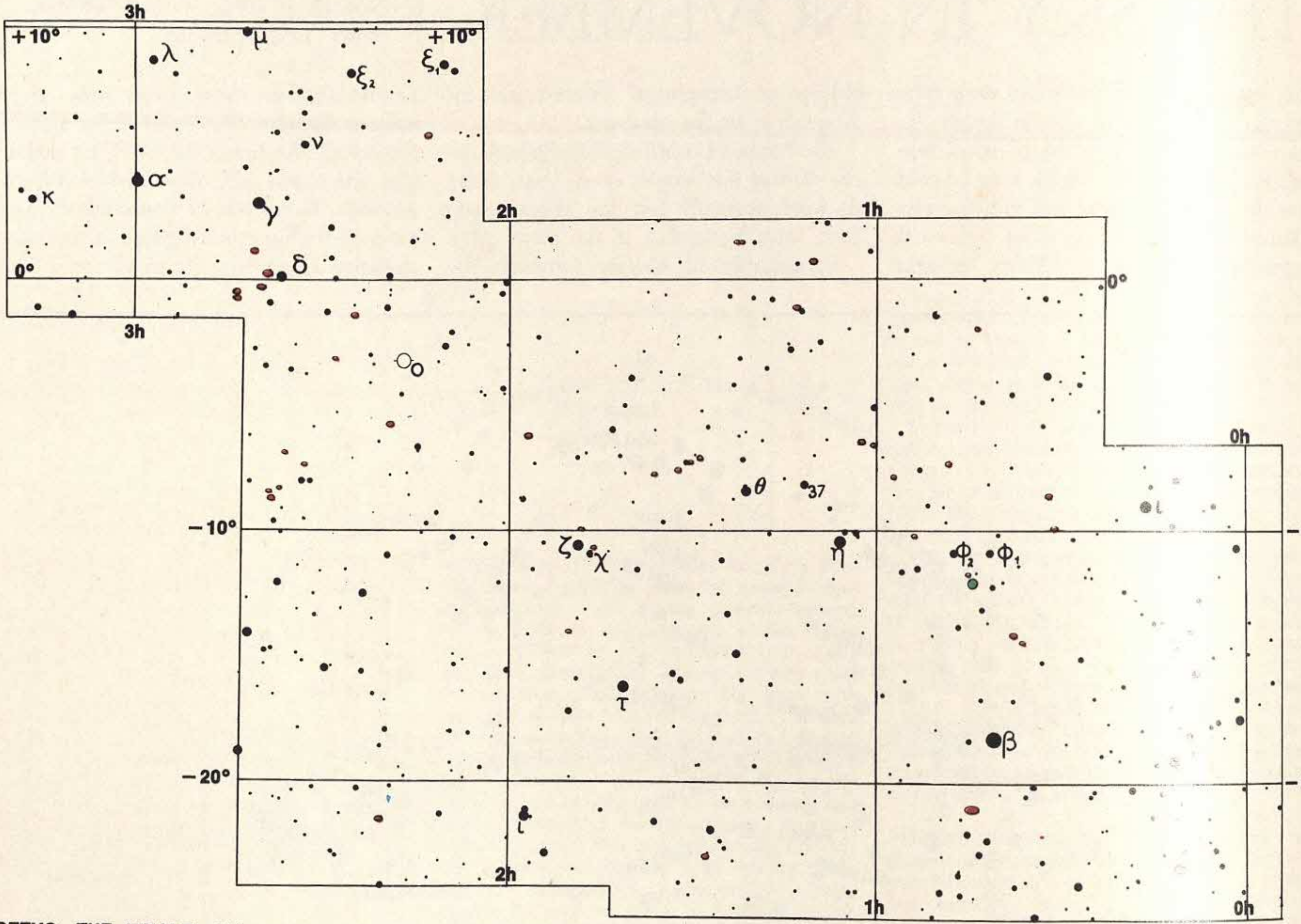
Periodically—at 33-year intervals—the Leonid showers have been truly magnificent displays. The spectacular meteor shower of November 12, 1833, for example, was seen all over eastern North America. Hundreds of thousands of meteors, radiating from a point in the constellation Leo, were observed.



THE NOVEMBER SKY—This star chart shows the disposition of the principal constellations with respect to the four cardinal points of the compass and the horizon at nine o'clock on a November evening. The constellations that were high on the southern horizon during the preceding month are still visible for a while on the western horizon. Thus, Cygnus (the Swan), Aquila (the Eagle), and Lyra (the Lyre) are seen as they are about to set in the northwest. In the southwest Aquarius (the Water Carrier) is still in the sky, and Pegasus is even higher above the horizon. The observer, by referring to Pegasus, can easily find the constellation Andromeda.

Cassiopeia shines almost at the zenith, and Cepheus lies between Cassiopeia and the celestial pole. The most spectacular constellations at nine o'clock in the evening are Cetus (the Whale), Aries (the Ram), and Andromeda—named in the order in which they are found, from low to high, above the southern horizon.

To the northeast is the omnipresent Ursa Major (the Great Bear), but at 9:00 P.M. in November this constellation is quite low on the horizon. To the east and southeast the marvellous constellations that brighten the winter sky are rising, but in November they can be observed only much later, after midnight. Among them, Gemini (the Twins), Orion (the Hunter), Auriga (the Charioteer), Taurus (the Bull), and Eridanus (the River) can already be seen. Nevertheless, the constellations of interest in November are those that are found near the meridian.



CETUS, THE WHALE—This constellation is one of the most extensive in the sky. In declination it extends from 10° north of the equator to 25° south. In right ascension (east-west direction), it is almost as vast as Pisces and Aries, the two zodiacal constellations to the north.

Because it is located far from the Milky Way, Cetus does not have many stars. Nevertheless, many interesting curiosities in the constellation can be seen with a telescope. The stars Alpha (α) and Beta (β), in particular, make for worthwhile observations. These stars vary so much in brightness that α is not always the brightest star in the constellation, but is sometimes surpassed by β. Viewed through binoculars or a small telescope, α appears as a very beautiful pair of stars. The primary star has a magnitude of 2.5, and the secondary has a magnitude of 5.5; the former is orange, and the latter is blue. Together they form a splendid pair, equal in beauty to Albireo (β Cygni). The constellation contains many other double stars that can be seen through a small telescope or even through binoculars.

The star identified as number 37 and located between Eta (η) and Theta (θ) is also a double with components of magnitudes 5.1 and 7, respectively. The distance between the stars is 50″ of arc; therefore, the pair may be distinguished with the aid of a small telescope. Most observers enjoy studying binaries not only because they are pairs, but also because they are often distinguished by striking color contrasts.

Gamma (γ) is a double that is not easily observed, but that can serve as a test of the optical quality of the telescope. Near the 3rd-magnitude primary star—about 2.6″ away—is its companion of magnitude 6.8. Observation of this beautiful pair requires an optically perfect telescope with a mirror (or objective lens) having a diameter of at least 10 cm (about 4 in.).

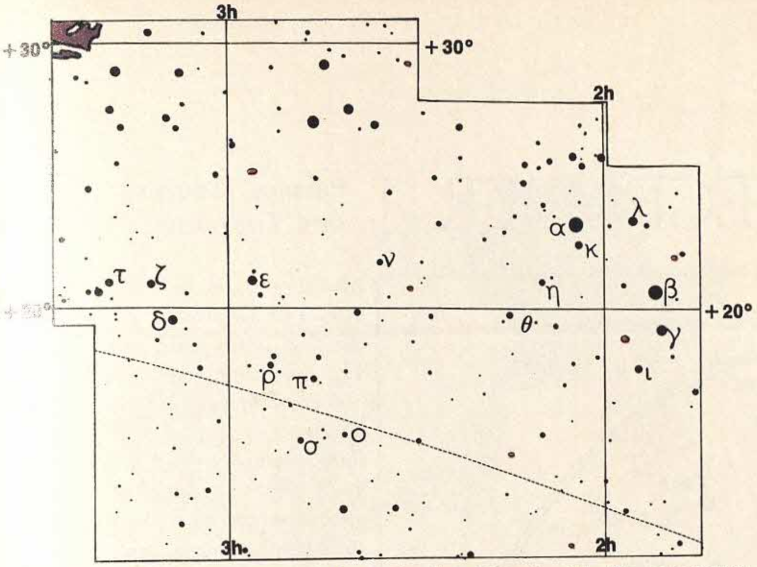
With an instrument capable of capturing light from stars of the 12th magnitude—that is, an instrument with an objective of 15 cm (about 6 in.), capable of resolving stars only 0.5″ apart—an observer can see at least 40 double stars in this constellation.

With a telescope an observer can also find some of the brighter extragalactic nebulas in the constellation. A group of five nebulas is visible a little to the left of Delta (δ); one is located about 3° below Beta (β). The other nebulas are considerably more difficult to observe both because they are less luminous than those already mentioned and because they are not near any stars whose alignments would indicate their exact positions.

The real marvel of the constellation Cetus is the star Omicron (o). This star varies so greatly in brightness that the seventeenth-century German astronomer Johan Hevelius named it *Mira*, a Latin word meaning "wonderful, extraordinary, or astonishing." Mira was the first star recognized to be variable (by Fabricius in 1596). Mira varies in brightness from a maximum magnitude of 1.7 to a minimum magnitude of 9.6; that is, Mira's light is about 1,500 times as bright at maximum brilliance as it is at minimum. This is equivalent to the difference between the brightness of the sun as seen at noon and its weak light as seen at sunset.

Mira is an irregular variable in that it does not always reach magnitude 1.7 at maximum nor does it always diminish in brightness to magnitude 9.6 at minimum. The variation is usually limited between the 4th and 9th magnitudes. Hence, there are times when the star sparkles in the sky and other times when it is invisible to the naked eye and can be seen only with the aid of powerful binoculars. Mira is irregular also in the duration of its period of variation. The average cycle of variation is 331 days, but the period may be as short as 200 days or as long as 400 days. The star is found near δ; the surrounding stars can be used as references for determining the brightness of Mira and for ascertaining which point the star has reached in its cycle.

With a good telescope, an observer can see the light of a small planetary nebula between Beta (β) and Phi (φ).



ARIES—This is a small zodiacal constellation far from the Milky Way and poor in celestial objects. Three stars visible to the naked eye sketch the figure of the Ram. Nowhere in Aries is there a nebula that is visible through a small telescope. By way of compensation, however, the constellation does contain some double stars, one of which is most notable. To see this star, Gamma (γ), an observer must use a telescope having an objective of at least 50 cm (about 20 in.), with a magnifying power of at least 80 X; with such an instrument, the observer can discern the two stars comprising this binary. The stars, which are almost identical in color and almost equal in brightness, have magnitudes 4.2 and 4.4. They are situated 8.6″ apart, and for this reason a good instrument is required to separate them. The English physicist Robert Hooke discovered that γ was a binary when he was studying the motion of a comet in 1664.

Another striking double star is Lambda (λ), whose components are of magnitudes 4.7 and 6.7. The primary and secondary stars are separated by 38″ of arc, a sufficient distance to permit them to be seen as a double with the aid of a small glass only.

Another star of interest is Pi (π), whose magnitude is 4.9; located 3.3″ away is a small companion star of magnitude 8.4. To distinguish the secondary star requires the use of a telescope with an 8- to 10-cm (about 3- to 4-in.) objective. With the same instrument, at a distance of 25″ (a distance that can be distinguished with any instrument having a magnifying power of 40 X), a star of the 10th magnitude can be seen. In other words, π is a triple star—considerably less common than a binary, but not rare. Probably, however, the stars are not linked by gravitational attraction into a single system; the third, more distant than the others, is most likely only an apparent companion of the other two stars.

The aforementioned objects are the only curiosities in the constellation Aries that can be seen through a small telescope.

ANDROMEDA AND TRIANGULUM—These two constellations are situated adjacent to each other, and on the sky chart they are drawn together. The constellations extend only a short distance from the Milky Way, and they are quite rich in stars and star clusters. The most remarkable sight in Andromeda is an extragalactic nebula, the only one visible to the naked eye in northerly latitudes. (In the Southern Hemisphere, the two Magellanic Clouds are also visible; but, to see them at a reasonable height above the horizon, an observer must travel as far south as the equator.)

The star α Andromedae constitutes one corner of the square formed by a group of stars in the constellation Pegasus; to the east, along the line determined by the upper side of the square, are the three main stars of Andromeda —Alpha (α), Beta (β), and Gamma (γ). The extragalactic nebula is above β, as shown on this chart, in a line with Mu (μ) and Nu (ν). A clear, moonless night is required for the nebula to be seen with the unaided eye or the telescope; under these favorable conditions, it can be seen easily. (Once again, the observer should note that he can see this object better by looking a little to the side of the nebula than he can by fixing his attention directly on it.)

This great nebula in Andromeda is usually identified in astronomical literature as M31 (object number 31 in Messier's catalog); it is actually a spiral galaxy, estimated to be about 2 million light-years distant and believed to be quite similar to the Milky Way Galaxy, but somewhat smaller. For telescopic observation of M31, best results will be obtained by using the least magnification available for a particular instrument; for example, the least magnification of a telescope with a 15-cm (about 6-in.) objective is 20 X. Even a magnification of 30 X or 40 X will show the splendor of this outstanding nebula.

On a clear night, binoculars or a telescope will show the nebula extending more than 2° in right ascension; in declination, it is less extensive, about 0.5°. Telescopic photographs, on the other hand, show the nebula to be much larger than it appears by direct observation; its diameter is about 150 million light-years.

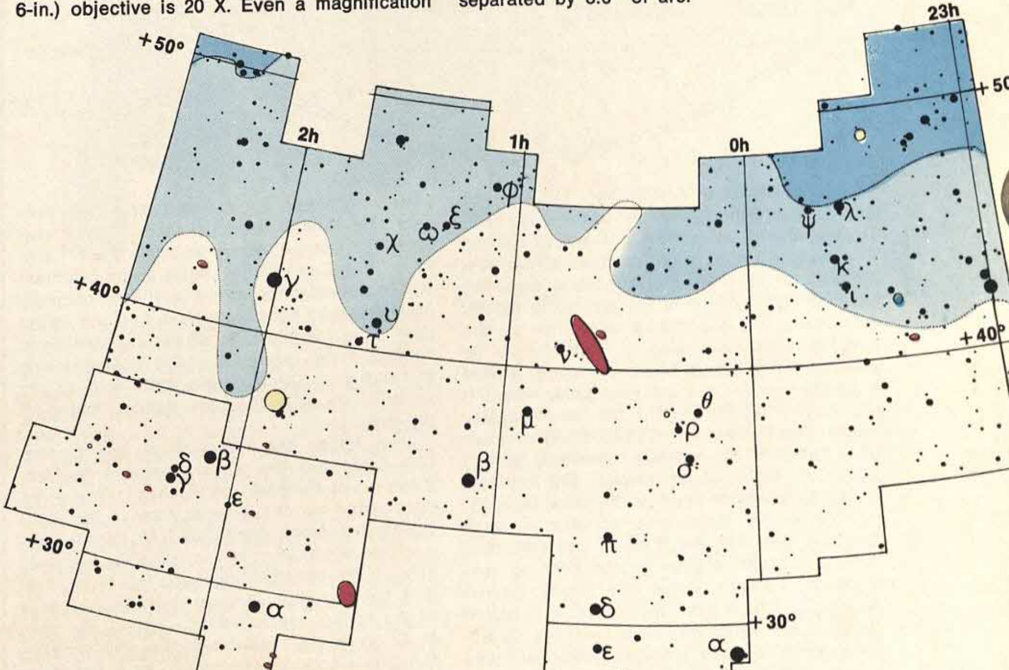
Beside M31, in the position shown on the chart, is another smaller nebula, located at a distance probably no greater than its own diameter. This nebula, an elliptical galaxy, is usually identified as M32. In the field of the telescope, it appears as a spot of light, bright in the center and dimmer toward the edges.

Among the stars in Andromeda, the most notable is certainly Gamma (γ), which is made up of a star of the 3rd magnitude and another of the 5th magnitude. The primary star is yellow and the secondary is blue, and the color contrast is one of the most striking in the sky. The distance between the primary and secondary stars in γ is slightly more than 10″; hence, a small telescope suffices to resolve the double into its two components. What is unusual, however, is that the 5th-magnitude star is itself a double; so the whole system is actually a triple. To distinguish the components of the secondary star requires an optically superior telescope with an objective at least 30 cm (about 12 in.) in diameter.

In the small constellation Triangulum, which is southeast of Andromeda, the most interesting sight is the extragalactic nebula located between Alpha (α) Trianguli and Tau (τ) Andromedae. This nebula, usually identified as M33, is invisible to the naked eye, but it can be seen with the aid of a small telescope or binoculars. It is less extensive and dimmer than M31 in Andromeda, but it is still interesting for its size. Next to the great Andromeda nebula, it is the largest extragalactic nebula visible in the Northern Hemisphere.

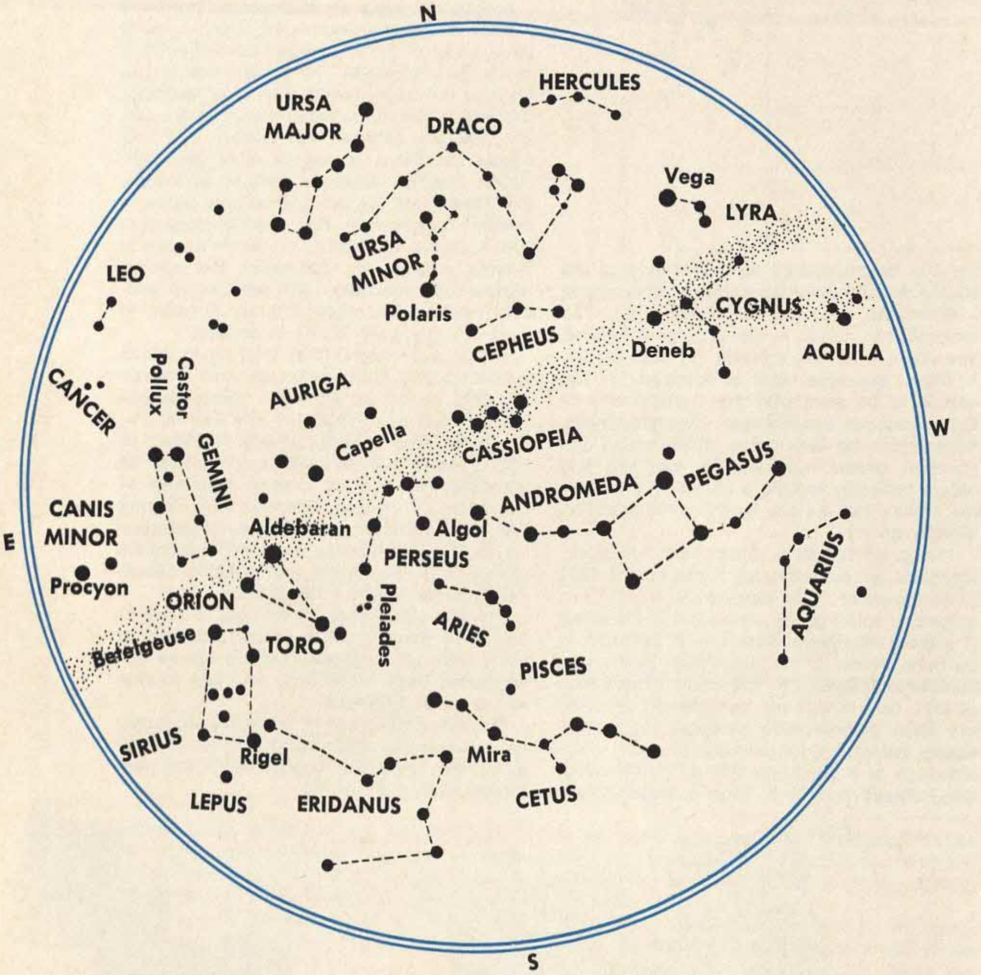
The star cluster near β Trianguli is another object of interest. This cluster consists of many stars, the brightest of which can be distinguished with binoculars, and the weaker with a small telescope.

The only double star in Triangulum that may be conveniently observed is Iota (ι); it comprises two stars of magnitudes 5 and 6.4, separated by 3.6″ of arc.



THE SKY IN DECEMBER

Perseus, Taurus, and Eridanus



THE DECEMBER SKY—This star chart shows the constellations visible above the horizon in December. In the northwest the constellation Cygnus (the Swan) is no longer in a favorable position for observation. Cepheus is declining from its high position of the preceding month, and Draco (the Dragon) is rather low on the horizon. Cassiopeia, also in decline from its position along the meridian, is moving toward a position under the celestial pole, where it will be during the spring months. Pegasus, Pisces (the Fishes), and Cetus (the Whale) are also found in the western quadrant, setting night by night closer toward the horizon. These constellations can be observed throughout the month, but not at too late an hour; the best time to view them is between nine o'clock and ten o'clock in the evening. Andromeda, Perseus, Aries (the Ram), Taurus (the Bull), Auriga (the Charioteer), Orion (the Hunter), and Lepus (the Hare)—all are clearly seen on or near the meridian. Some of these constellations will be described in detail.

Gemini (the Twins), Canis Major (the Great Dog), and Canis Minor (the Little Dog) are three constellations characterized by the brilliant light of their principal stars—Castor and Pollux in Gemini, Sirius in Canis Major, and Procyon in Canis Minor. Sirius is the brightest star in the celestial sphere, and the spectacle of its twinkling light is marvelous to see in the dark of a starry night. These constellations constitute the group of winter constellations that make up Orion's train; their light shines so brilliantly that they are easily located in the sky.

Ursa Major (the Great Bear) and Cancer (the Crab) are low on the eastern horizon; these constellations may be seen during the succeeding months or even later in the night during December. After 9:00 P.M. Regulus appears on the eastern horizon; it is the brightest star in the constellation Leo (the Lion), and it is the star that announces the appearance of the spring constellations. Just as the train of Orion is associated with the cold months, the appearance of Leo serves as a harbinger of spring. Those constellations best observed during December are Perseus, Taurus, and Eridanus (the River).

In many parts of North America, the arrival of December is accompanied by the first really cold weather of winter. The cold nights present a problem for observers inasmuch as instruments kept in a warm room must be allowed ample time to adapt to the cold air. On the other hand, the winter nights are usually the clearest of the year, and the winter constellations abound in striking celestial objects, many of which can be observed with the unaided eye as well as with the telescope.

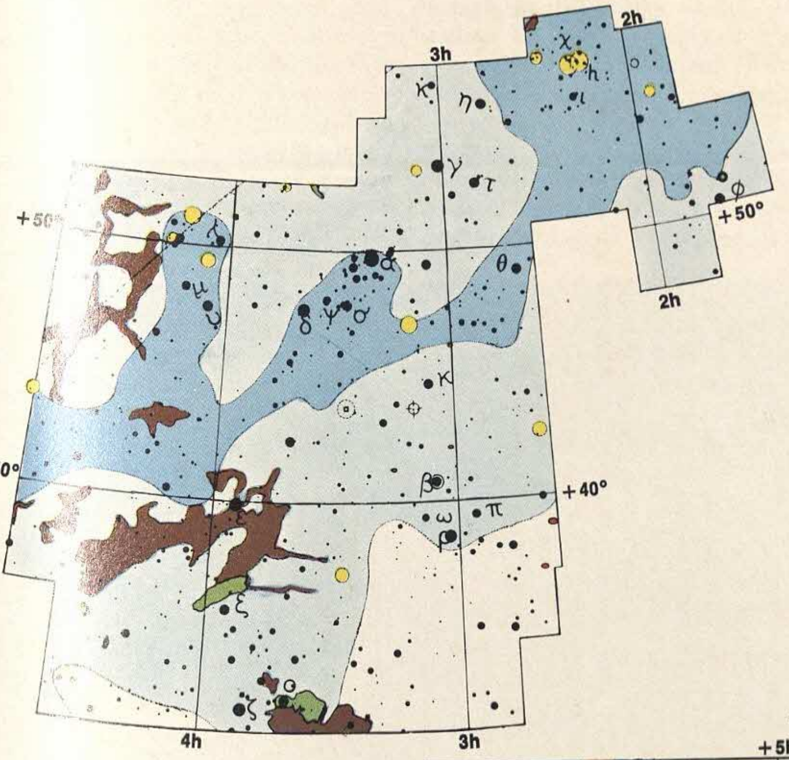
This article, in keeping with the other articles on the sky during different months, begins with a description of the general aspect of the sky and proceeds to more detailed descriptions of the interesting objects to be found in certain constellations.

PERSEUS—Of all the constellations in the sky, Perseus contains one of the richest arrays of celestial objects. It extends along the Milky Way to the high northern latitudes; consequently, during its most favorable period, it lies well above the horizon, where it is easily visible through the telescope. With the Milky Way in the background, the region is rich in stars that may best be viewed with telescopes of large objective diameter and low magnifying power.

Among the most interesting objects in the constellation are the galactic or open star clusters, 11 of which are visible with the aid of medium-power telescopes. Two clusters are especially bright and can be seen with the naked eye, appearing as faint symmetrical spots; ancient astronomers, believing them to be stars, designated them Chi (χ) and **h.** Even with the naked eye, however, there is no danger of confusing the clusters with stars; the designations were given as a convenience to celestial cartographers at a time when little was known about galactic clusters. To the eye, the double cluster **h** and χ appears as a fragment broken off the Milky Way; in reality it consists of stars that are much closer than those forming the background of the Galaxy. This double cluster may be observed easily with all types of viewing instruments, from simple binoculars to the most powerful telescopes. In a telescope with a 25-cm (about 10-in.) objective and a magnifying power of 30 X to 40 X, the two clusters fill the field with more than a thousand bright stars. The extraordinary nearness of this double cluster is also a curiosity.

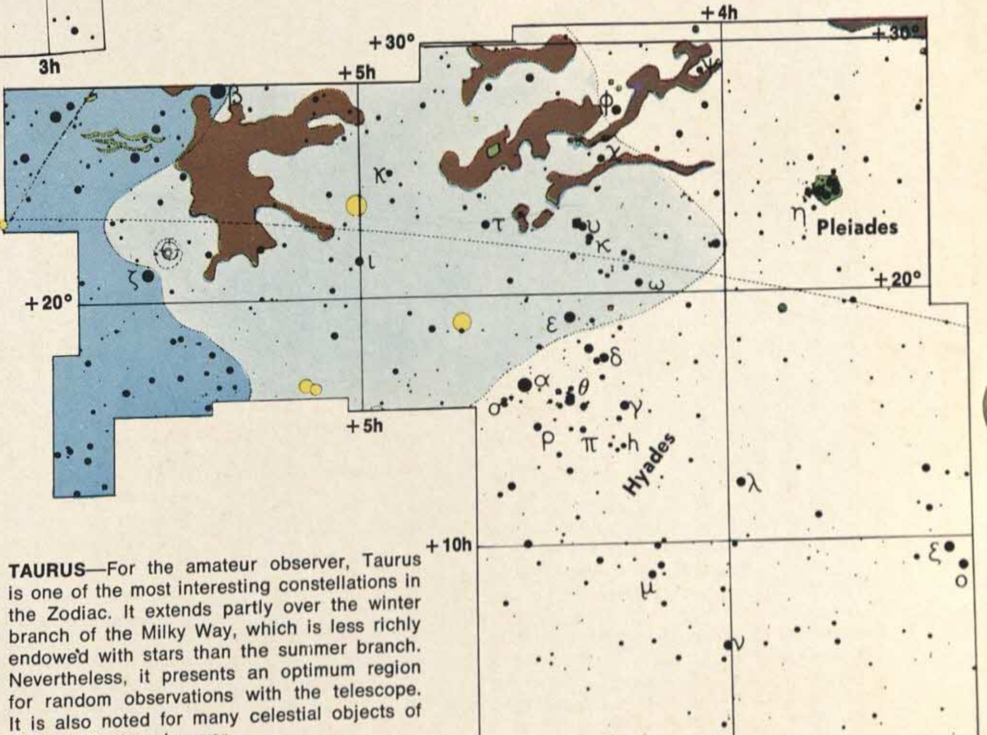
The brightest star in Perseus is Mirfah, identified as Alpha (α); this star of magnitude 1.9 is about 190 light-years from Earth. It is in line with the two upper stars of the square of Pegasus and the three principal stars in Andromeda.

Algol, the star identified as Beta (β), is another noteworthy object in the constellation Perseus. It is located beneath and a little to



the west of α. Observation of Algol with the naked eye or with a telescope reveals no particularly interesting characteristics; however, careful observation, night after night, shows that periodically the star's luminosity changes. In about three hours, Algol decreases in magnitude from about 2.1 to about 3.3; this variation occurs with clocklike regularity in a period of about 68.9 hours. Because Arab astronomers did not know the cause of this variability, they gave the star the name *al-guhl* (Algol), the ghoul or demon star. Actually Algol is an eclipsing binary; its variation in luminosity is caused by the revolution of a companion star of extremely low luminosity. Each time the secondary star comes between Algol and the Earth, Algol is eclipsed. This system contains a third star that is not eclipsed.

The chart shows a small planetary nebula above the star designated Phi (φ); this nebula can be seen with a good telescope, which will also reveal many dozens of double stars in the constellation. Theta (θ) is a double, comprising a star of magnitude 4.2 and its companion of magnitude 10; the two components, located 15.4″ apart, are distinguishable with a small telescope. Eta (η) consists of a 4th-magnitude star accompanied by a star of magnitude 8.5 at a distance of 28″ of arc. Omicron (o) provides an excellent test for a telescope; its primary star is of the 4th magnitude and its secondary star is of magnitude 8.5, with the components located only 1″ apart. Zeta (ζ) is made up of a star of magnitude 2.8 and another of magnitude 9.3, separated by about 12.5″. Epsilon (ε) is composed of stars of magnitudes 2.9 and 8.0, separated by a distance of 8.8″. All of these double stars, except o, can be observed with a small telescope.



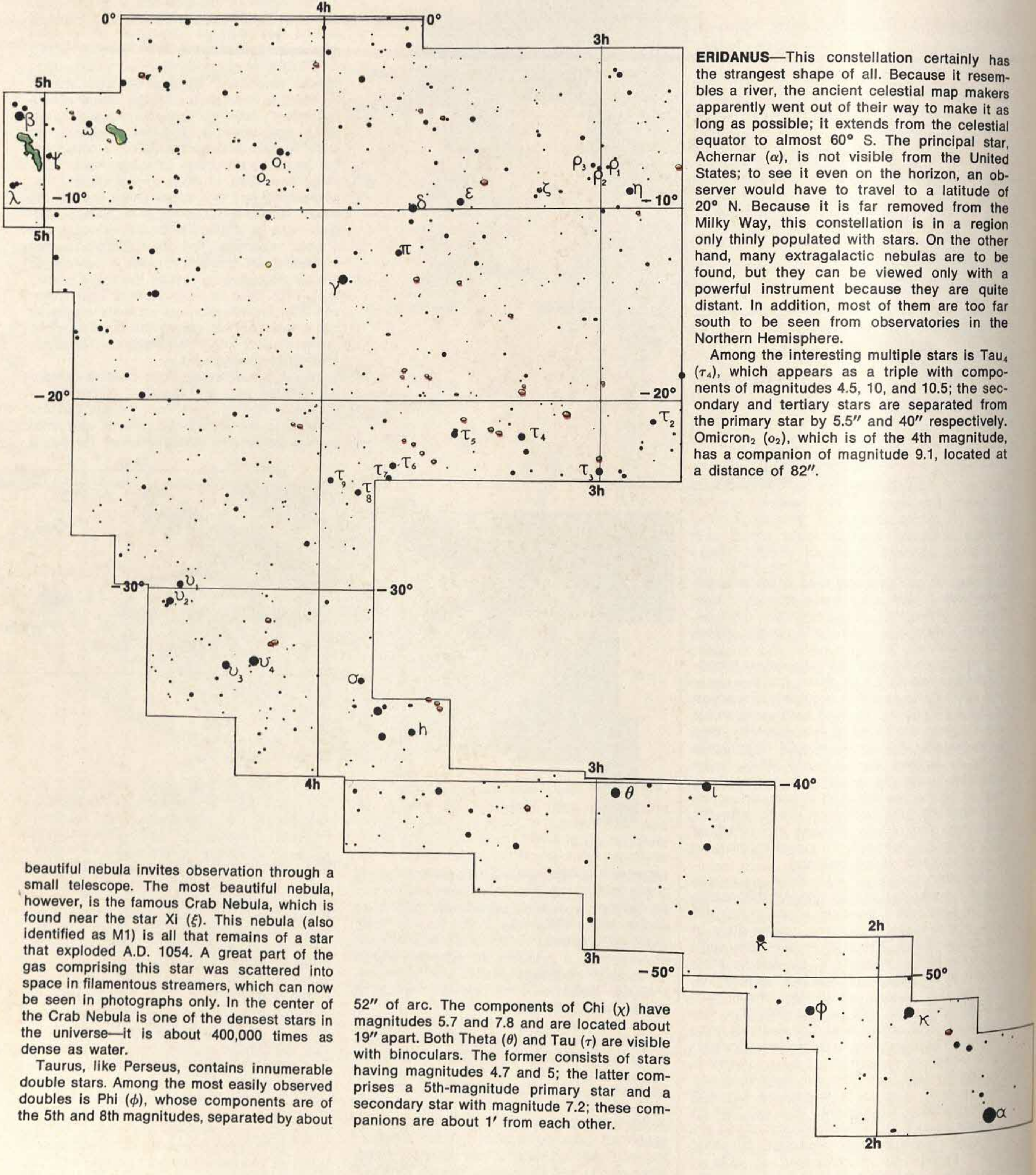
TAURUS—For the amateur observer, Taurus is one of the most interesting constellations in the Zodiac. It extends partly over the winter branch of the Milky Way, which is less richly endowed with stars than the summer branch. Nevertheless, it presents an optimum region for random observations with the telescope. It is also noted for many celestial objects of interest to the observer.

The two most remarkable objects—the star clusters known as the Hyades and the Pleiades—are clearly visible to the naked eye. The cluster of the Hyades is found immediately east of the principal star, Aldebaran, which is designated Alpha (α). This 1st-magnitude star of the red-giant type is an impressive body about 100 times as large as the sun. Notwithstanding the nearness of the Hyades group, Aldebaran is not part of the cluster. The Hyades can be clearly seen with the naked eye, but the group is so extensive that it cannot be included in a single field of the telescope; only low-power binoculars will contain the entire cluster.

The cluster of the Pleiades is considerably more restricted than the Hyades, and it can be viewed well through binoculars or a small telescope. The Pleiades may serve as a test for the quality of observation: on a clear night without moonlight, an observer can discern six stars in the group with the naked eye; a person with excellent eyesight may distinguish seven and, under exceptional conditions, as many as ten. Without benefit of a telescope, the German astronomer Johannes Kepler correctly described 14 stars in this cluster; unfortunately, very few people have such acute vision. More stars—as many as several hundred—can be distinguished with binoculars or a small telescope. The chief difficulty comes in finding an instrument with a sufficiently low magnification to contain the entire cluster in its field. With an instrument of high power and low magnification, an observer may also see a weak nebula among the principal stars in the cluster; this nebula becomes apparent at once in photographs.

Taurus contains other star clusters besides the Hyades and the Pleiades. Northeast of Aldebaran, for example, two clusters that are invisible to the naked eye may be seen with a small telescope. Above the star Psi (ψ), a beautiful nebula invites observation through a small telescope. The most beautiful nebula, however, is the famous Crab Nebula, which is found near the star Xi (ξ). This nebula (also identified as M1) is all that remains of a star that exploded A.D. 1054. A great part of the gas comprising this star was scattered into space in filamentous streamers, which can now be seen in photographs only. In the center of the Crab Nebula is one of the densest stars in the universe—it is about 400,000 times as dense as water.

Taurus, like Perseus, contains innumerable double stars. Among the most easily observed doubles is Phi (ϕ), whose components are of the 5th and 8th magnitudes, separated by about 52″ of arc. The components of Chi (χ) have magnitudes 5.7 and 7.8 and are located about 19″ apart. Both Theta (θ) and Tau (τ) are visible with binoculars. The former consists of stars having magnitudes 4.7 and 5; the latter comprises a 5th-magnitude primary star and a secondary star with magnitude 7.2; these companions are about 1′ from each other.



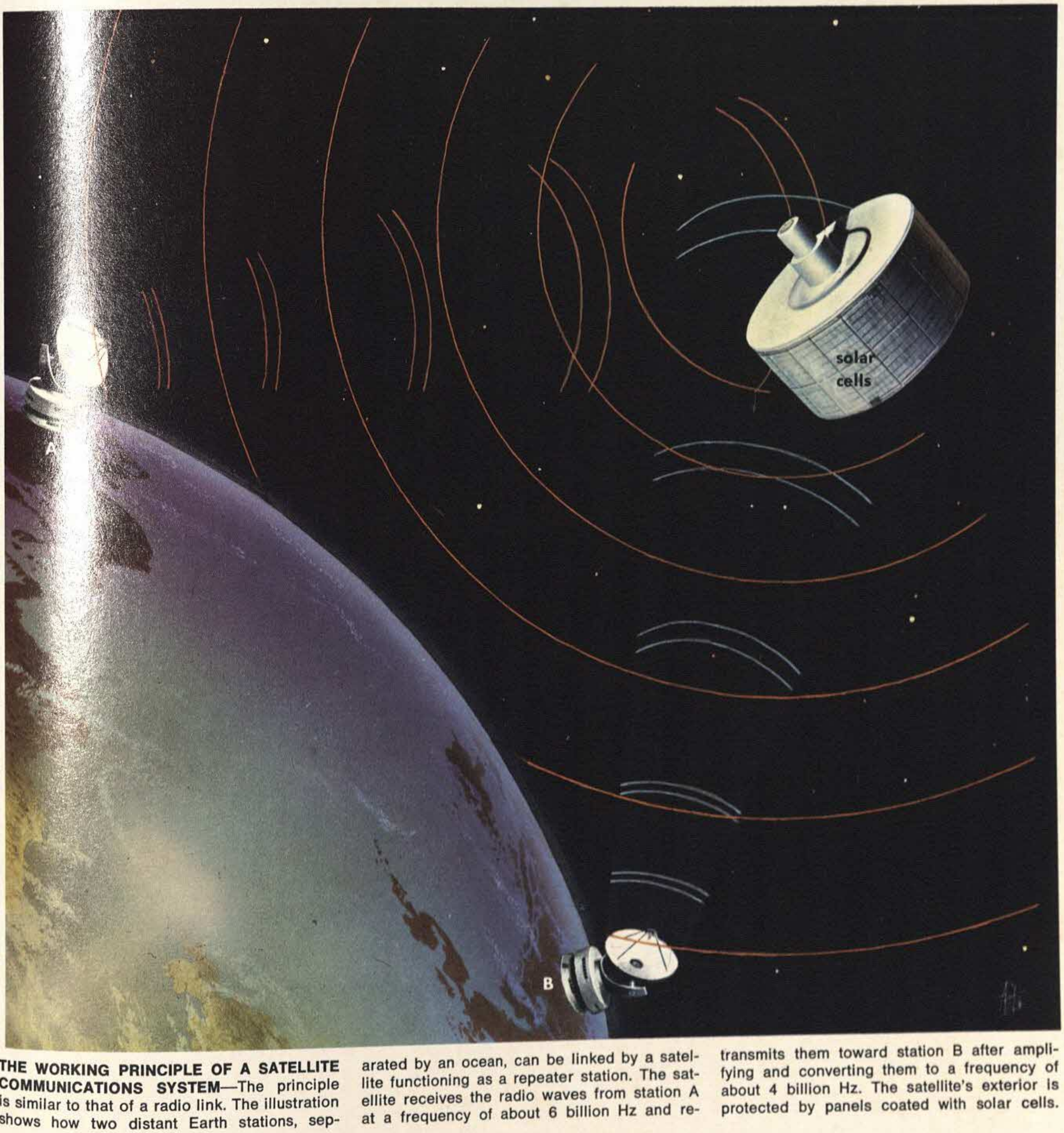
ERIDANUS—This constellation certainly has the strangest shape of all. Because it resembles a river, the ancient celestial map makers apparently went out of their way to make it as long as possible; it extends from the celestial equator to almost 60° S. The principal star, Achernar (α), is not visible from the United States; to see it even on the horizon, an observer would have to travel to a latitude of 20° N. Because it is far removed from the Milky Way, this constellation is in a region only thinly populated with stars. On the other hand, many extragalactic nebulas are to be found, but they can be viewed only with a powerful instrument because they are quite distant. In addition, most of them are too far south to be seen from observatories in the Northern Hemisphere.

Among the interesting multiple stars is Tau₄ (τ₄), which appears as a triple with components of magnitudes 4.5, 10, and 10.5; the secondary and tertiary stars are separated from the primary star by 5.5″ and 40″ respectively. Omicron₂ (o₂), which is of the 4th magnitude, has a companion of magnitude 9.1, located at a distance of 82″.

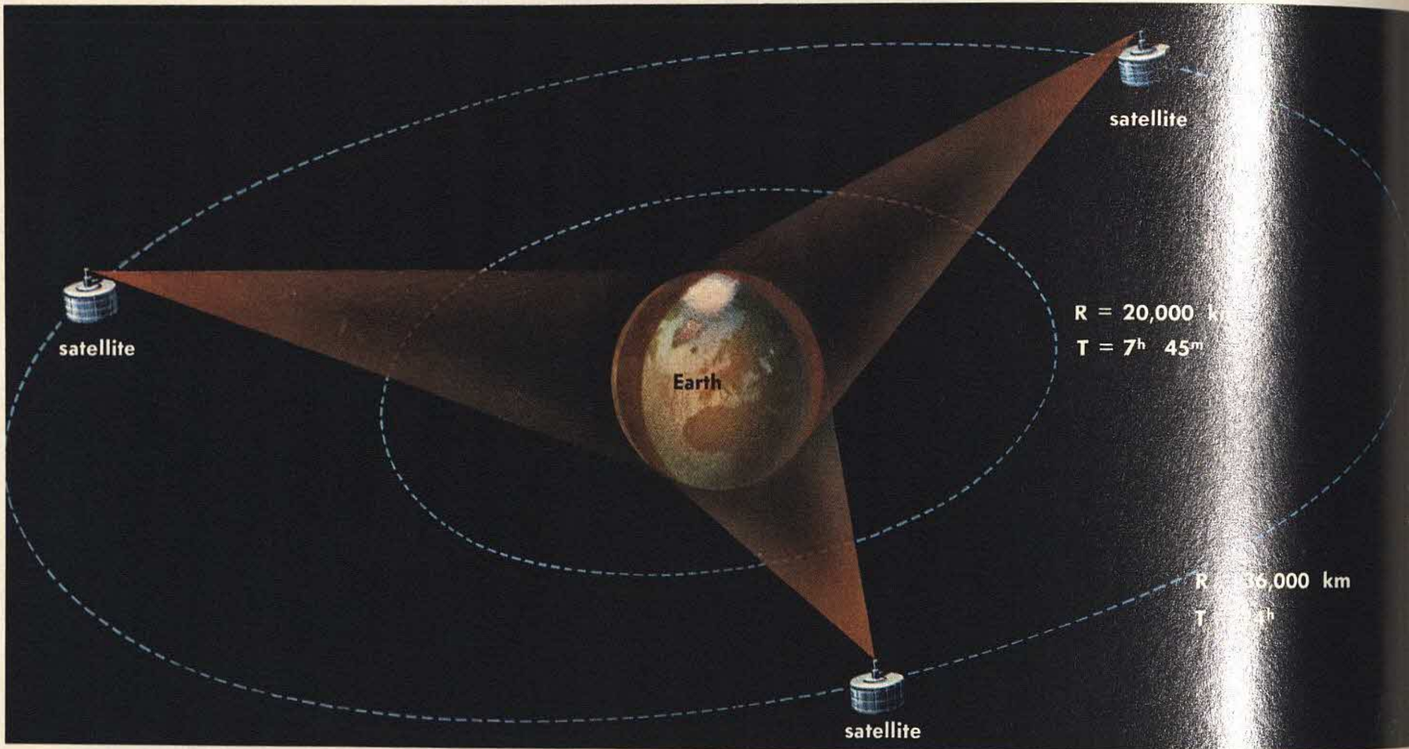
SPACE COMMUNICATIONS | the role of artificial satellites

Since World War II, exceptional progress in electronic and space technology has enabled the nations of the world to continuously expand their telecommunication network. Primarily, this rapid expansion has been the result of the incessant demand for new telephone circuits, and the development of ever-broadening radio and television services. The great increase in the number of transmitting stations has made it necessary for the various stations to be linked effectively with one another—a technological problem requiring exhaustive research. It is predictable that this expansion will continue even faster in the future, partly because of the need for such new services as the transmission of data, educational television, and other communications developments.

Such developments will necessarily involve a comparable refinement in existing intercontinental communications. While the main branches of present-day continental networks in the more developed countries make use of coaxial cables, or high-capacity microwave links,



THE WORKING PRINCIPLE OF A SATELLITE COMMUNICATIONS SYSTEM—The principle is similar to that of a radio link. The illustration shows how two distant Earth stations, separated by an ocean, can be linked by a satellite functioning as a repeater station. The satellite receives the radio waves from station A at a frequency of about 6 billion Hz and retransmits them toward station B after amplifying and converting them to a frequency of about 4 billion Hz. The satellite's exterior is protected by panels coated with solar cells.



THE CHOICE OF ORBIT—Placing a stationary satellite into orbit at a particular altitude requires that the satellite have a tangential velocity sufficient to produce a centrifugal force exactly equal to the force of gravity at that altitude. Since the force of gravity decreases with altitude, so does the required velocity. The period of rotation **T** in minutes can be expressed as a function of the radius of the orbit **R** in km by the following formula:

$$T = \sqrt{R^3/3.7 \times 10^7}.$$

Illustration 2 shows some combinations of altitude and rotation periods. An altitude of 36,000 km (about 22,300 mi.) above the equator corresponds to the Earth's rotation period of 24 hours. A satellite in equatorial orbit at this altitude is called synchronous; it is said to be stationary because it appears to be fixed in the celestial sphere as seen from the Earth's surface.

Satellites at lower altitudes rotate more rapidly and the direction of the station's antennas thus has to be varied to follow the satellite. Since a satellite at a lower altitude is seen from a smaller area of the Earth's surface, the number of satellites needed for a global system increases as altitude decreases.

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there is considerable difficulty in adopting such techniques for communications between continents. The great distances involved, and the fact that huge areas of desert or ocean often have to be crossed, make links of this sort extremely expensive, or even impracticable. For transoceanic links, special coaxial cables incorporating amplifiers have been designed to continue functioning for many years on the ocean floor. Such special cables, however, can handle only a fraction of the number of conversations transmitted simultaneously by overland cables. They cannot, at present, transmit television programs. Likewise, transoceanic radio links cannot be established since each repeater station must be within sight of the preceding station.

Recent progress in space research has led to the placing of communications satellites in orbit around the Earth, thus providing a solution to many telecommunication problems. These satellites are visible simultaneously from several Earth stations, situated great distances apart on different continents. The satellites are equipped with receiving and transmitting antennas and electronic apparatus that allow them to receive radio signals from one Earth station and retransmit them, suitably amplified, to the next station.

THE PRINCIPLE OF SATELLITE COMMUNICATIONS

The principle behind the functioning of satellite communications is the same as that of microwave radio links. However, only one repeater station is required in the link between two Earth stations, and this is the orbiting satellite itself. The use of very high-frequency waves, such as microwaves, has many advantages:

it permits the utilization of highly directional antennas that relay the available signals in very narrow beams, on the same principle as used in light beacons; it allows transmission in extremely wide frequency bands, thus permitting a great number of simultaneous telephone conversations or several simultaneous television programs; it allows transmission, with very small attenuations, through the atmosphere and the ionosphere; and it allows drastic reduction of radiation interferences present in the same range of frequencies as the faint signal transmitted by the satellite. In fact, the radiations originating from the Earth are picked up to only a negligible extent by station antennas pointed at the sky. In the superhigh frequencies used, the radiations generated by the molecules of the atmosphere or arriving from cosmic space are very small indeed.

A major advantage of satellites is that a satellite can be used to link up more than two Earth stations simultaneously, provided that all stations are simultaneously visible to one another. This method is known as "multiple access." Each Earth station is allocated one or more transmission frequencies, which are modulated into telephone or television signal frequencies. The satellite receives them all and retransmits them simultaneously. As a result, each station simultaneously receives the signals coming from all the others. It is thus possible to establish a system of global communications. Telephone conversations or television programs can be transmitted by all the Earth stations that are in sight of the same satellite. Every station on the Earth can thus be linked, provided that enough orbiting satellites are appropriately spaced around the Earth.

SATELLITES OF THE PRESENT AND THE FUTURE

Technology today is so far advanced that Intelsat-III satellites have been put into orbit at an altitude of about 36,000 km (about 22,300 mi). They weigh about 110 kg (about 242 lbs). One was launched in May 1969 over the Pacific Ocean, and one was launched in January 1970 over the Atlantic Ocean. These satellites are equipped with two units of receiver-transmitters (transponders) having an overall bandwidth of 500 MHz (megahertz units) and capable of amplifying signals for retransmission with a power of 10 watts per receiver-transmitter. Each satellite has a communications capability of 1,200 high-quality voice circuits or four television channels, or a combination of the two; and each satellite is able to serve as a radio link around nearly half the world. The satellites were placed in synchronous orbit, which means that the orbital velocity matches the rotational speed of the Earth; thus, the satellites are, in effect, stationary. In 1970 the Communications Satellite Corporation (Comsat) had five Intelsat III satellites in service, over the Atlantic, Pacific, and Indian oceans. The lifetime of operation of each was expected to be about five years.

It was planned to replace the Intelsat IIIs with Intelsat IV satellites, each weighing about 1,112 kg (2,450 lbs) and each having a capacity of 5,000 telephone circuits. The newer satellites have a diameter of 3 m (about 10 ft) and weigh 448 kg (about 1,000 lbs). Each will be equipped with 12 receiver-transmitters having a transmission power of 10 watts. The new giants will be stationary, and antenna positions of Earth stations will, therefore, stay virtually fixed.

A great advantage of stationary satellites is that they orbit at an altitude sufficient for three of them to cover the entire surface of the Earth. The higher cost of launching is thereby offset by the small number of satellites required. Linking up a large number of Earth stations with only a few of these high payload satellites makes such communications economically feasible despite the high cost and complexity of the Earth stations, which are even more expensive than the construction and launching of the satellites. The increased power and range available from the new satellites will make it possible to use less costly Earth stations. Thus, stationary satellites may eventually be used even for communications within a single continent and for the direct distribution of television programs to relay stations serving a continent. In fact, the realm of television broadcasting is where communications satellites probably offer their greatest promise. Current satellites are low powered, highly directional, and dependent on large, powerful receiving stations. These ground receivers transmit television by microwave or land lines to a local broadcasting station whose own transmitters beam the television image to home television receivers. There is a real possibility, however, that soon satellites will be broadcasting from stationary orbit to home receivers. To accomplish this, high broadcast power is required in the satellite as well as a large antenna. The U.S. National Aeronautics and Space Administration (NASA) was developing such a satellite in 1970. The spacecraft will use an antenna that is about 9 m (30 ft) in diameter, the largest ever deployed in space. This satellite, Applications Technology Satellite F (ATS-F), is scheduled to be used in an attempt at mass education in India. Receiving television signals from a transmitter in India, ATS-F will rebroadcast from space to approximately 5,000 Indian villages. Each village will be equipped with a low-cost, large-screen television receiver. The broadcast satellite has great potential for the benefit of India's 500 million people.

The Symphonie program, a cooperative venture of France and West Germany, called for the launching of a satellite in 1972. The space booster to be used is the Europa II, constructed under the direction of the European Launcher Development Organization.

ABBREVIATIONS

A	ampere
Å	Angstrom unit
abs	absolute
a-c	alternating current (as an adjective)
amu	atomic mass unit
atm	atmosphere
at. wt	atomic weight
AU	astronomical unit
avdp	avoirdupois
Bev	one billion electron volts
bhp	brake horsepower
bhp-hr	brake horsepower-hour
bp	boiling point
Btu	British thermal unit
C	temperature Celsius; temperature Centigrade
c	candle
cal	calorie
cfm	cubic feet per minute
cfs	cubic feet per second
cgs	centimeter-gram-second (system)
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
coef	coefficient
colog	cologarithm
cos	cosine
cot	cotangent
cp	candlepower
csc	cosecant
cu	cubic
cu ft	cubic foot
db	decibel
d-c	direct current (as an adjective)
doz	dozen
E	electromotive force
e	the base of the system of natural logarithms
ev	electron volt
F	temperature Fahrenheit
fp	freezing point
fpm	feet per minute
fps	feet per second
ft	foot; feet
ft^2	square foot
ft^3	cubic foot
ft-c	footcandle
ft-lb	foot-pound
G	universal gravitational constant
g	gram
gal	gallon
g-cal	gram-calorie
gpm	gallons per minute
gps	gallons per second
hr	hour
$h\nu$	photon energy
hp	horsepower
Hz	hertz (cycles per second)
I	electric current
ID	inside diameter
in.	inch
$in.^2$	square inch
$in.^3$	cubic inch
in.-lb	inch-pound
ips	inches per second
j	joule
K	temperature Kelvin (absolute)
kcal	kilocalorie
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg/m^3	kilograms per cubic meter
kgps	kilograms per second
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	liter; lumen
lat	latitude
lb	pound
lb-ft	pound-foot
lb/ft^2	pounds per square foot
lb/ft^3	pounds per cubic foot
lb-in.	pound-inch
l-hr	lumen-hour
lin ft	linear foot
log	logarithm (common)
$\log_e$	logarithm (natural)
long.	longitude
m	meter; minute (time, in astronomical circles)
m^2	square meter
m^3	cubic meter
ma	milliampere
Mev	one million electron volts
mg	milligram
mh	millihenry
mi	mile
mi^2	square mile
min	minute
m-kg	meter-kilogram
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
$m\mu$	millimicron
mph	miles per hour
mphps	miles per hour per second
mv	millivolt
N	Avogadro's constant
n!	factorial *n*
OD	outside diameter
oz	ounce
pH	rating on acid-alkaline scale
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
R	temperature Reaumur; resistance
RA	right ascension
rpm	revolutions per minute
rps	revolutions per second
sec	secant; second
sin	sine
sp gr	specific gravity
sq	square
tan	tangent
V	volt
VA	volt-ampere
W	watt; work
yd	yard
yd^2	square yard
yd^3	cubic yard

SCIENTIFIC SYMBOLS AND ABBREVIATIONS

α	alpha particle
β; β^-	beta particle
β^+	positron
γ	gamma radiation
Δ	a small change; heat
λ	wavelength; radioactive-decay constant
ma	milliampere
μc	microcurie
μf	microfarad
$\mu in.$	microinch
μm	micron
$\mu\mu$	micromicron
$\mu\mu f$	micromicrofarad
ν	frequency; neutrino
π	3.14159; osmotic pressure
Σ	the sum of
σ	nuclear cross section (barns); area
Ω	electrical resistance (ohms)
ω	angular speed; angular velocity
$'$	minute (angular measure)
$''$	second (angular measure)
♂	male
♀	female
$>$	is greater than
$<$	is less than
$\propto$	is proportional to
∞	infinity
$\sqrt{}$	square root of
$^\circ$	degrees; temperature; angle measurement (example, 30°)
[ ]	molar concentration
$+$	positive electric charge; mixed with; plus
$-$	negative electric charge; single covalent bond; minus
$=$	equals; double covalent bond; produces
$\neq$	does not equal
$\equiv$	triple covalent bond
$\rightarrow$	produces; forms; chemical reaction
$\rightleftarrows$	reversible chemical reaction
$\uparrow$	gas produced by a chemical reaction
$\downarrow$	precipitate produced by a chemical reaction
*	radioactive substance (follows symbol of element; example, Cl^*)

THE
ILLUSTRATED SCIENCE
DICTIONARY

Free Flight to Gyrostatics

KEY TO PRONUNCIATION

The diacritical marks are:

ə	b*a*nan*a*, *a*but
ᵊ	preceding l, m, n as in battl*e*
ə̇	*e*lectric
ər	f*ur*ther
a	m*a*t
ā	d*ay*
ä	c*o*t, f*a*ther
au̇	n*ow*, *ou*t
e	b*e*t
ē	b*ea*t
i	t*i*p
ī	b*i*te
j	*j*ob, *g*em
ŋ	si*ng*
ō	b*o*ne
ȯ	s*aw*, *a*ll
ȯi	c*oi*n
th	*th*in
t͟h	*th*en
ü	r*u*le, f*oo*l
u̇	p*u*ll, w*oo*d
ue	German h*ü*bsch
u̅e̅	French r*ue*
yü	*u*nion
zh	vi*si*on

ˈ mark preceding the syllable with strongest stress.
ˌ mark preceding a syllable with secondary stress.

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free flight \'frē 'flīt\

AERONAUTICS and ASTRONAUTICS. The unpowered flight of an aircraft or rocket.

A rocket is in FREE FLIGHT *after the power has been shut off.*

free state \'frē 'stāt\

CHEMISTRY. The condition of an element or a substance when it is not mixed or combined with any other elements or substances.

Because of fluorine's high chemical activity, it is difficult to keep it in a FREE STATE.

freezing point \'frēz-iŋ 'pȯint\

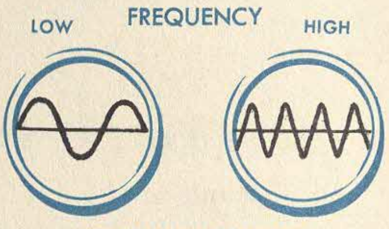
PHYSICS. The temperature at which a liquid becomes a solid; identical with the temperature at which the solid melts.

The FREEZING POINT *of water is 0° C., but that of iron is 1,535° C.*

frequency \'frē-kwən-sē\ *n.*

PHYSICS. The number of waves, cycles or vibrations that leave or arrive at a given point each second. Frequency is most often applied to alternating-current electricity and to light or sound waves.

A high-fidelity amplifier attempts to reproduce each sound FREQUENCY *accurately and without distortion.*

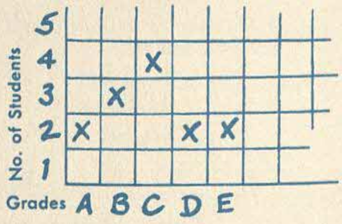


OSCILLOSCOPE SCREENS

frequency distribution \'frē-kwən-sē ˌdis-trə-'byü-shən\

MATHEMATICS. A statistical array exhibiting the number of items, in a given set of data, that belong to each of a group of subclasses, or intervals.

A teacher may make a FREQUENCY DISTRIBUTION *that shows the number of students in a class whose grades fall within given intervals.*



FREQUENCY DISTRIBUTION

frequency modulation \'frē-kwən-sē ˌmäj-ə-'lā-shən\

ENGINEERING. The technique of transmitting information by radio waves in which the frequency of the carrier wave is varied by the input, resulting in a signal that is relatively free from static and other interference. The method differs from early radio techniques in which the carrier wave amplitude is varied, or modulated; *abbr.* FM; see *amplitude modulation.*

Commercial television stations utilize FREQUENCY MODULATION *for both picture and sound transmission.*

friable \'frī-ə-bəl\ *adj.*

1. CHEMISTRY. Pertaining to any chemical substance that can be easily pulverized or made into a powder. 2. EARTH SCIENCE. Referring to rocks that are soft and that crumble readily.

Most calcium compounds are FRIABLE.

FROND (FERN)

friction \'frik-shən\ *n.*

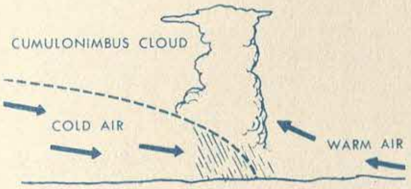
PHYSICS. The force that resists the moving of an object over the surface of another object or through another substance.

When motion overcomes FRICTION, *heat energy is produced.*

Frigid Zone \'frij-əd 'zōn\

EARTH SCIENCE. Either of the two polar zones: the region between the North Pole and the Arctic Circle, or between the South Pole and the Antarctic Circle.

In the FRIGID ZONE, *the sun's rays always strike at an oblique angle, resulting in a climate that is very cold in winter and cool or cold in summer.*



FRONT (COLD FRONT)

frond \'fränd\ *n.*

BOTANY. The leaf structure of a fern that bears the reproductive cells on its surface.

The FROND *of a fern is found in the sporophyte generation.*

front \'frənt\ *n.*

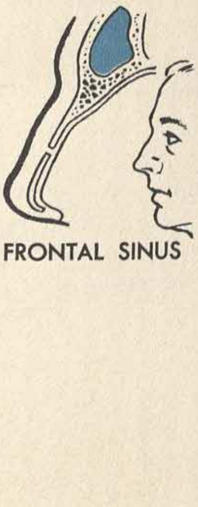
EARTH SCIENCE. An imaginary line on the earth, or a line on a map, representing the surface between the air masses; also, the contact area between two air masses.

A FRONT *is classified as warm or cold, according to which air mass is overtaking the other.*

frontal lobe \'frənt-ᵊl 'lōb\

ANATOMY. One of the five parts of either of the hemispheres of the brain. It lies in front of the deep cleft and slightly forward from the upper border of the hemisphere.

The motor area of the brain is located in the FRONTAL LOBE.



FRONTAL SINUS

frontal sinus \'frənt-ᵊl 'sī-nəs\

ANATOMY. One of the air cavities that connects with the nasal cavities and that is located behind the frontal bone of the skull above the nose.

An inflammation of a FRONTAL SINUS *is one type of sinusitis.*

frost \'fröst\ *n.*

EARTH SCIENCE. Ice crystals formed by the condensation of water vapor on surfaces having a temperature of 32° F. or colder.

FROST is formed by the same process as dew, but at subfreezing temperatures.

frost action \'fröst 'ak-shən\

EARTH SCIENCE. A mechanical weathering process in which the alternate freezing and thawing of water in the cracks in rocks breaks them into smaller and smaller particles.

FROST ACTION occurs most in areas where the daily temperatures frequently vary above and below the freezing point.

fruit \'früt\ *n.*

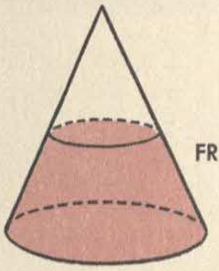
BOTANY. The ripened ovary of a flower that contains one or more seeds and often includes certain other tissues, as the red pulp of a strawberry; also, the edible portion of a plant that is produced from a flower, as an apple.

Trees have been developed by grafting to produce more than one kind of FRUIT.

frustum \'frəs-təm\ *n.*

MATHEMATICS. That portion of a solid, usually a cone or a pyramid, between two planes cutting through it or between the base of the solid and an intersecting plane parallel to it.

The volume of the FRUSTUM of a circular cone can be computed if the altitude and the radii of the bases are known.



FRUSTUM

FSH

An abbreviation for follicle-stimulating hormone. See *follicle-stimulating hormone.*

f/stop system \'ef-,stäp 'sis-təm\

PHYSICS. A numerical system corresponding to various sizes of the adjustable diaphragm that regulates the amount of light passing through a camera lens. F/stops are determined by dividing the focal length of the lens by the diameter of the diaphragm opening.

Most exposure meters are designed to be read in the numbers of the F/STOP SYSTEM.

f/STOP SYSTEM

fuel cell \'fyü(-ə)l 'sel\

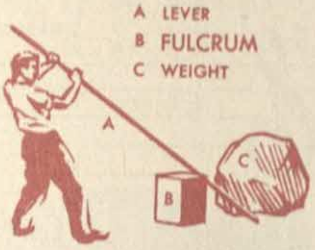
CHEMISTRY and ENGINEERING. A device that produces electricity directly from a chemical reaction.

An ordinary flashlight battery is really a type of FUEL CELL.

fuel injection \'fyü(-ə)l in-'jek-shən\

ENGINEERING. A process of forcing fuel from a pump into the cylinder of an internal combustion engine or into the air at the cylinder intake. Such injection allows control of the proportion of fuel and air and increases engine efficiency.

In a diesel engine, FUEL INJECTION *breaks the oil into a fine spray when it enters the cylinder and is accomplished in approximately $\frac{1}{100}$ second.*



fulcrum \'fu̇l-krəm\ *n.*

PHYSICS. The fixed point around which a lever turns or pivots.

The elbow joint of a human arm acts as a FULCRUM.

fuller's earth \'fu̇l-ərz 'ərth\

CHEMISTRY and EARTH SCIENCE. A group of earthlike materials resembling clay, used to absorb color from fats and oils.

The largest deposits of FULLER'S EARTH *are found in the United States, Japan and England.*

full moon \'fu̇l 'mün\

ASTRONOMY. The phase of the moon when the sun and the moon are on opposite sides of the earth, and the whole moon appears to be illuminated.

A FULL MOON, *which rises in the early evening, occurs about a week after its first-quarter phase.*

fulminating powder \'fu̇l-mə-ˌnāt-iŋ 'pau̇d-ər\

CHEMISTRY. Any highly-explosive compound that contains the fulminate radical ONC in its molecule; also, a salt of fulminic acid.

Mercury fulminate is a FULMINATING POWDER *used to detonate TNT.*

fumarole \'fyü-mə-ˌrōl\ *n.*

EARTH SCIENCE. A hole, a crack or an opening in volcanic regions of the earth through which fumes, vapors and hot gases escape; also, a spring or a geyser that spurts jets of gaseous vapors.

Gases such as carbon dioxide, carbon monoxide, hydrogen sulfide and sulfur dioxide escaping from a FUMAROLE *may have an injurious effect on nearby plant and animal life.*

function \'fəŋ(k)-shən\ *n.*

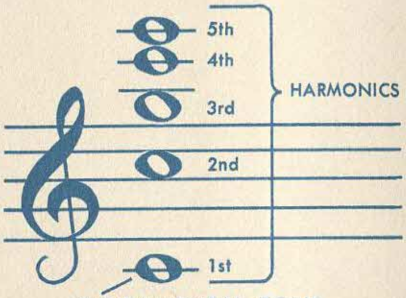
MATHEMATICS. A set of ordered pairs in which no two second elements are paired with the same first element.

The FUNCTION *f defined by the equation* $y = 5x + 2$, *or* $f(x)$

= 5x + 2, is called a linear function because its graph is a straight line.

fundamental tone \ˌfən-də-ˈment-ᵊl ˈtōn\
PHYSICS. The lowest note or pitch that is made by a freely-vibrating source of sound.

Harmonics, or overtones, are some multiple of the frequency of the FUNDAMENTAL TONE.



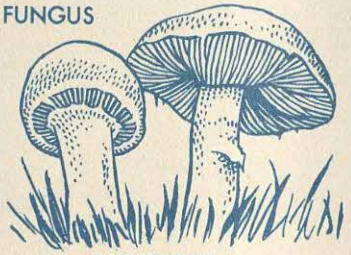
FUNDAMENTAL TONE

fundamental units \ˌfən-də-ˈment-ᵊl ˈyü-nəts\
PHYSICS. Arbitrary units of mass, length and time that are used as the basis for a system of derived units. Three principal sets are MKS (meter-kilogram-second), cgs (centimeter-gram-second), and fps (foot-pound-second).

The watt is a unit of power based on the MKS FUNDAMENTAL UNITS.

fungicide \ˈfən-jə-ˌsīd\ *n.*
CHEMISTRY and MEDICINE. Any substance used to destroy fungi or the spores of fungi.

A FUNGICIDE *is usually used to treat ringworm.*

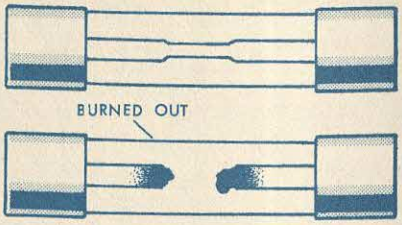


fungus \ˈfəŋ-gəs\ *n.*
BIOLOGY. Any of the subkingdom Thallophyta that contains no chlorophyll and depends upon another plant or animal for its food.

A FUNGUS *that lives on dead organic matter is called a saprophyte.*

fuse \ˈfyüz\ *n.*
ENGINEERING. A protective device that opens an electric circuit when a dangerously-large current flows through it.

A typical electric circuit in a house requires a 15-ampere FUSE.



FUSE (AUTOMOTIVE)

fusion \ˈfyü-zhən\ *n.*
1. PHYSICS. The process by which two or more particles join to make one particle; also, the process by which the nuclei of two light atoms join to form a single nucleus of a heavier atom (nuclear fusion) and in so doing release a large amount of energy compared with that given off by chemical reactions between two atoms. 2. BIOLOGY. The coming together of two or more cell nuclei, as in fertilization.

Two deuterons can be made to undergo FUSION *to produce one helium nucleus, one free neutron and 3.2 million electron volts of energy.*

G

g \'jē\ *n.*

ASTRONAUTICS and PHYSICS. The symbol for acceleration of a falling body due to the earth's gravity. Quantitatively, at the earth's surface, one g is approximately 32 feet, or 980 cm., per second per second.

In space travel, man is subjected to accelerations greater and less than one G.

Milky Way as seen from earth

galaxy \'gal-ək-sē\ *n.*

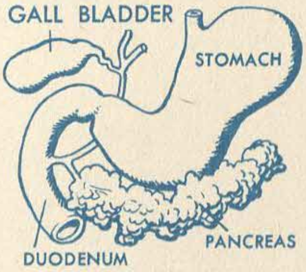
ASTRONOMY. Any of the systems of millions of stars, nebulae, gases and dust.

The GALAXY *to which our solar system belongs is called the Milky Way.*

gale \'gāl\ *n.*

EARTH SCIENCE. A wind with a velocity of from 32 to 63 miles per hour; a wind of force 7, 8, 9 or 10 on the Beaufort scale.

A moderate GALE *causes trees to sway, a strong gale causes branches to break and a whole gale frequently uproots trees.*



gall bladder \'gȯl 'blad-ər\

ANATOMY. A small, pear-shaped sac that is attached to the liver and that collects liver bile.

Bile passes from the GALL BLADDER *into the duodenum, where it is used in the digestion of fats.*

galvanism \'gal-və-ˌniz-əm\ *n.*

PHYSICS. That branch of physics concerned with the behavior and effects of electric currents.

GALVANISM *was named after the Italian physician Luigi Galvani.*

galvanize \'gal-və-ˌnīz\ *v.*

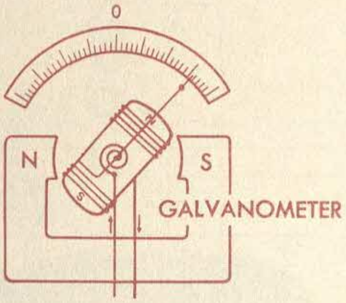
CHEMISTRY. To deposit a layer of zinc on iron or steel surfaces to prevent rusting. The process is generally accomplished by dipping the object to be coated in a bath of molten zinc.

To GALVANIZE *steel, it is first necessary to remove any rust, dirt or grease adhering to it.*

galvanometer \ˌgal-və-'näm-ət-ər\ *n.*

CHEMISTRY and PHYSICS. An instrument used to measure an electric current or, in some cases, simply to detect a current.

The operation of a GALVANOMETER *depends upon the magnetic effect of an electric current.*



gamete \gə-'mēt\ *n.*

BIOLOGY. Any mature reproductive cell that, when united with another, forms a zygote such as a fertilized egg.

Either an unfertilized egg or a sperm is called a GAMETE.

gametophyte \gə-'mēt-ə-ˌfīt\ *n.*

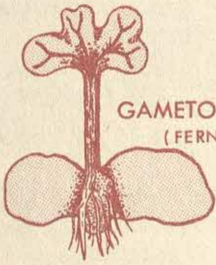
BOTANY. The sexual generation that produces gametes in those plants with alternating generations, as contrasted with the sporophyte generation that produces asexual spores.

A fern is a plant that, during one stage of its life cycle, can be classified as a GAMETOPHYTE.

gamma globulin \'gam-ə 'gläb-yə-lən\

MEDICINE. The part of the blood serum that contains most of the disease-fighting antibodies.

GAMMA GLOBULIN *is used to inoculate those who have been exposed to certain epidemic diseases.*


GAMETOPHYTE
(FERN)

gamma rays \'gam-ə 'rāz\

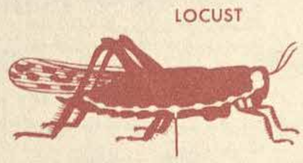
PHYSICS. Electromagnetic waves of extremely short wavelength (very high frequency), having their origin in the nucleus of an atom.

GAMMA RAYS *have great energy, travel with the speed of light and penetrate matter readily.*

ganglion \'gaŋ-glē-ən\ *n.*

ANATOMY. Any collection, or mass, of nerve cells that serves as a center from which nerve impulses are transmitted.

Some animals have a GANGLION *instead of a brain.*



gangue \'gaŋ\ *n.*

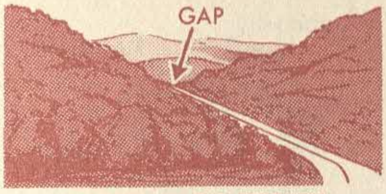
EARTH SCIENCE. Nonvaluable minerals and earth that are found with valuable ores in a deposit or vein.

Quartz frequently occurs in a GANGUE.

gantry \'gan-trē\ *n.*

ASTRONAUTICS. A movable cranelike structure, used in assembling and servicing rockets or missiles.

The GANTRY *is rolled away from a rocket just prior to blast-off.*



CUMBERLAND GAP THROUGH APPALACHIAN MOUNTAINS

gap \'gap\ *n.*

EARTH SCIENCE. A deep notch or ravine in a ridge or mountain chain.

The trail through the Cumberland GAP *in the Appalachian Mountains was used by many pioneers who settled the Midwest.*

gas \'gas\ *n.*

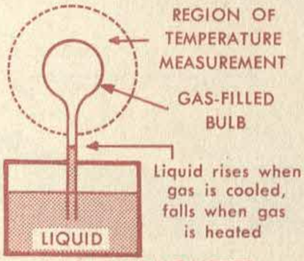
CHEMISTRY and PHYSICS. That one of the three states of matter (solid, liquid or gas) whose molecules move freely and whose mass will expand indefinitely, thus filling any container.

Any GAS *can be liquefied, generally by increasing the pressure on, and reducing the temperature of, the gas.*

gasoline \ˌgas-ə-'lēn\ *n.*

CHEMISTRY. A colorless, flammable liquid consisting principally of a mixture of hydrocarbons, heptane (C_7H_{16}), octane (C_8H_{18}) and nonane (C_9H_{20}).

Most GASOLINE *is produced from petroleum, although it can be manufactured from coal.*


REGION OF TEMPERATURE MEASUREMENT
GAS-FILLED BULB
Liquid rises when gas is cooled, falls when gas is heated
LIQUID

GAS THERMOMETER

gas thermometer \'gas thə(r)-'mäm-ət-ər\

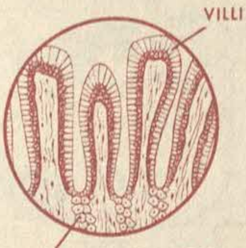
PHYSICS. An instrument for measuring temperatures by recording the reaction of gas to heating or cooling. Given a stable volume, a gas will change its pressure, or, given stable pressure, will change its volume, when subjected to temperature variation. Either change can be measured for determining temperature.

Hydrogen or helium is commonly used in a GAS THERMOMETER.

gastric glands \'gas-trik 'glandz\

ANATOMY. The glands in the lining of the stomach that secrete gastric juice.

The inner coat of the stomach contains millions of tubular GASTRIC GLANDS.



GASTRIC GLANDS

gastric juice \'gas-trik 'jüs\

PHYSIOLOGY. A fluid secreted by the gastric glands of the stomach and containing enzymes and hydrochloric acid.

Pepsin, an enzyme of the GASTRIC JUICE, *can break down proteins only in the presence of an acid.*

gastrolith \'gas-trə-ˌlith\ *n.*

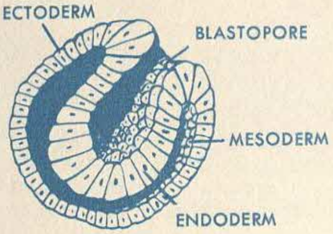
EARTH SCIENCE. Polished, well-rounded pebbles found with some dinosaur remains and believed to have been stomach stones.

A GASTROLITH *must be found along with skeletal remains in order to be properly identified.*

gastrula \'gas-trə-lə\ *n.*

ZOOLOGY. An early stage of a developing embryo, usually consisting of a sac composed of two layers of cells called the ectoderm and the endoderm.

The GASTRULA *encloses a central cavity with a single opening to the outside (the blastopore).*



GASTRULA

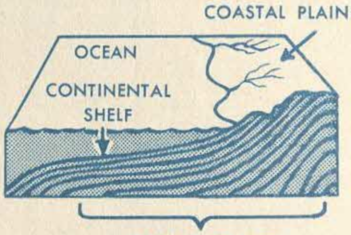
gauss \'gau̇s\ *n.*

PHYSICS. The unit of magnetic induction, or flux density, of a magnetic field, produced in a substance by a magnet or other source of magnetic field.

The GAUSS *should not be confused with the oersted, a unit of magnetic field intensity.*

GCA

Abbreviation for ground-controlled approach. See *ground-controlled approach.*



GEANTICLINE

geanticline \jē-'ant-i-ˌklīn\ *n.*

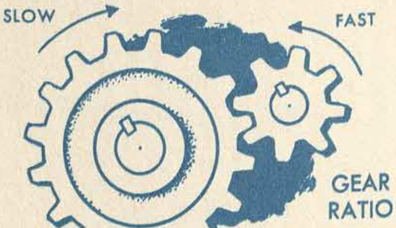
EARTH SCIENCE. A massive, symmetrical uplift in the crust of the earth. In cross section, it has the appearance of an inverted U or a semicircle.

A GEANTICLINE *has an area of hundreds of square miles.*

gear ratio \'gi(ə)r 'rā-(ˌ)shō\

PHYSICS. The mathematical expression of the relationship between the speed at which one shaft turns and the speed of another to which it is connected by gears.

A GEAR RATIO *of one to five means that one shaft revolves one time to five revolutions of the other.*



Geiger counter \'gī-gər 'kau̇nt-ər\

PHYSICS. An instrument that detects radioactivity and counts the ions formed by the particles of radiation that affect it. In one common form of Geiger counter, a tube contains a gas under low pressure that becomes ionized when a particle of radiation enters the tube. A momentary flow of current through the tube results, the flow being registered as a flash of light or a sound, and a count is recorded.

A GEIGER COUNTER *may be used in hunting deposits of uranium.*

gel \'jel\ *n.*

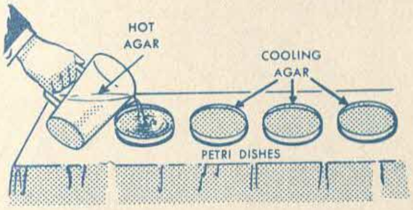
CHEMISTRY. A semisolid, jellylike substance in which colloidal particles are dispersed in a medium such as water or alcohol; a coagulated colloid.

Ordinary fruit jelly is an example of a GEL.

gelatin \'jel-ət-ᵊn\ *n.*

BIOLOGY and CHEMISTRY. A colorless, jellylike substance obtained from the tissues and bones of animals.

Because of its protein content, GELATIN *is used as a food.*



GELATION

gelation \ji-'lā-shən\ *n.*

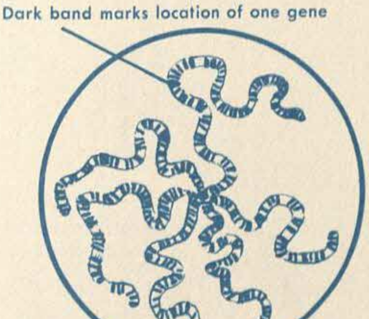
CHEMISTRY. The jelling, or solidifying, of liquid matter, generally as the result of cooling.

GELATION *takes place when a hot solution of agar is cooled.*

gene \'jēn\ *n.*

BIOLOGY. The unit of, or region in, a chromosome that governs the transmission of a specific hereditary trait. It is thought to be a molecule of DNA, or deoxyribonucleic acid.

A lethal GENE, *which is usually recessive, may cause the death of an organism during an early stage of its development.*


Dark band marks location of one gene

GENE FRUIT FLY CHROMOSOMES

gene pool \'jēn 'pül\

BIOLOGY. All of the types of genes present in a group of organisms whose members reproduce only among-themselves.

Gene mutation is a way in which a new trait is added to a given GENE POOL.

generate \'jen-ə-ˌrāt\ *v.*

To originate, produce or cause to come into existence.

To GENERATE *electrical energy, another source of energy, such as mechanical or chemical, must be used.*

generation \ˌjen-ə-'rā-shən\ *n.*

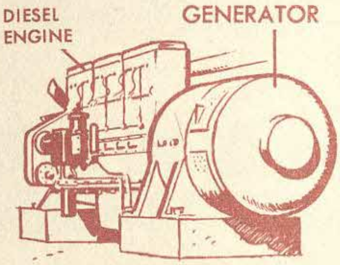
1. BIOLOGY. The process of reproducing new individuals in either plants or animals; also, a single stage in the succession of plants or animals. 2. CHEMISTRY and PHYSICS. The release of a gas in a chemical reaction; also, the conversion of mass to energy, as in a nuclear reaction; also, the conversion of energy from one form to another, as in the generation of electricity by a generator. 3. MATHEMATICS. The production of a geometric

figure by the motion of another figure, as the generation of a line by the movement of a point.

The GENERATION *of new individuals is characteristic of all forms of life.*

generator \'jen-ə-ˌrāt-ər\ *n.*
ENGINEERING. A machine or device that causes energy or substances to be changed from one form to another.

An automobile GENERATOR *supplies electricity for the car and is driven by power from the engine.*



genetic code \jə-'net-ik 'kōd\
BIOLOGY. The pattern or blueprint for development, embodying inherited characteristics, that is carried by the chromosomes of each living cell.

Scientists believe that the GENETIC CODE *lies in the sequence in which the chemical subunits adenine, thymine, guanine and cytosine occur along the DNA molecular helix.*

genetics \jə-'net-iks\ *n.*
BIOLOGY. The science concerned with heredity and variation.

Hybrid corn is one example of the results of the application of the principles of GENETICS.

genetic transduction \jə-'net-ik tran(t)s-'dək-shən\
BIOLOGY. The process in which hereditary material is transferred from one strain of bacteria to another through the action of a virus or bacteriophage.

The mechanism of GENETIC TRANSDUCTION *is being studied to learn more about inheritance and variations.*

genotype \'jē-nə-ˌtīp\ *n.*
BIOLOGY. The hereditary constitution of an organism including its total assortment of genes, both dominant and recessive.

Identical twins have the same GENOTYPE, *while fraternal twins seldom, if ever, have the same genotype.*

gentle breeze \'jent-ᵊl 'brēz\
EARTH SCIENCE. Wind moving across the earth at a velocity of 8 to 12 miles per hour. It is 3 on the Beaufort wind scale.

A GENTLE BREEZE *is strong enough to move leaves and small twigs.*

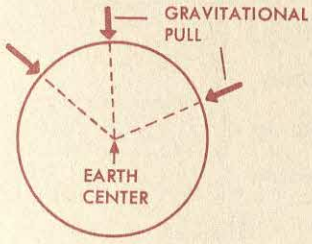
genus \'jē-nəs\ *n.*
BIOLOGY. A classification of plants or animals, generally on the

GENUS

PHYLUM: Arthropoda
CLASS: Insecta
ORDER: Diptera
FAMILY: Drosophilidae
GENUS: Drosophila
SPECIES: melanogaster
Common name: Fruit fly

basis of structure. It represents a subdivision of the larger family and is itself subdivided into species.

Canis is the name given to the GENUS *in which dogs are included.*



GEOCENTRIC

geocentric \ˌjē-ō-ˈsen-trik\ *adj.*

ASTRONOMY. Referring to the center of the earth as a point of reference; also, relating to the earth as a center.

The theory of a GEOCENTRIC *solar system was almost universally accepted until the time of Copernicus.*

geochemistry \ˌjē-ō-ˈkem-ə-strē\ *n.*

CHEMISTRY and EARTH SCIENCE. The branch of earth science concerned with the chemical composition of the earth's crust and the chemical changes within it.

GEOCHEMISTRY *helps to describe the processes of chemical and physical weathering of rock found in the crust of the earth.*

GEODE

geode \ˈjē-ˌōd\ *n.*

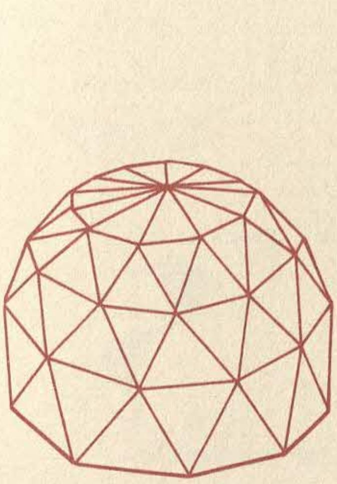
EARTH SCIENCE. A hollow, or partially-hollow, accumulation of mineral matter with a roughly-spherical form found most commonly in limestone beds and more rarely in shales. The inside wall is lined with crystals, often perfectly formed of quartz or calcite, that project inward toward the hollow center.

The usual GEODE *has a diameter of less than one foot.*

geodesic \ˌjē-ə-ˈdes-ik\ *adj.*

MATHEMATICS. Referring to the portion of a curve or line that is the shortest path between two points on a given surface.

The GEODESIC *line between two points on a sphere is the minor arc of the great circle passing through the two points.*



GEODESIC DOME

geodesic dome \ˌjē-ə-ˈdes-ik ˈdōm\

ENGINEERING. An igloo-shaped structure that can be built quickly and economically of lightweight materials, in any size. The framework is made up of numerous identical straight units combined over and over in the same simple geometrical pattern.

The structural strength of the GEODESIC DOME *lies in the slight but equal tension shared by all its components.*

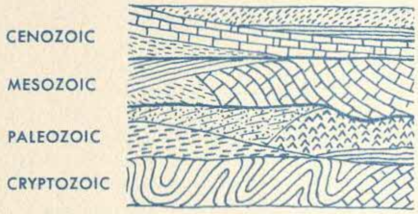
geodesy \jē-ˈäd-ə-sē\ *n.*

EARTH SCIENCE. A science concerned with the shape and dimensions of the earth.

Through GEODESY *we have learned that the earth is not exactly spherical.*

geography \jē-'äg-rə-fē\ *n.*
EARTH SCIENCE. The science that deals with the occurrence and distribution of the physical features, climates, mineral deposits and plants and animals of the earth in relation to its surface.

GEOGRAPHY *draws largely upon geology, astronomy, meteorology and biology for its data.*



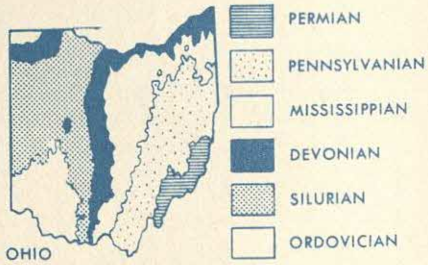
GEOLOGIC COLUMN

geologic column \ˌjē-ə-'läj-ik 'käl-əm\
EARTH SCIENCE. A column formed by rock units of various ages arranged in chronological order, from the oldest on the bottom to the youngest on the top.

A perfect GEOLOGIC COLUMN *is rarely seen in nature and is frequently represented by a generalized drawing.*

geologic map \ˌjē-ə-'läj-ik 'map\
EARTH SCIENCE. A map that shows not only the surface composition of an area but also the character and arrangement of the material beneath the surface. It also indicates the relative ages of what it portrays.

A GEOLOGIC MAP *is used in searching for oil deposits.*



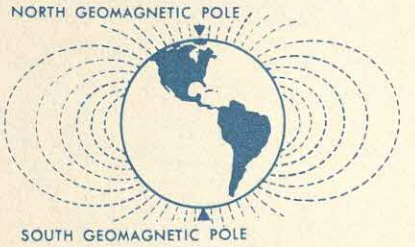
GEOLOGIC MAP

geologist \jē-'äl-ə-jəst\ *n.*
EARTH SCIENCE. A scientist who is especially concerned with studying the earth or investigating problems of the earth's origin, history, structure and composition.

A GEOLOGIST *accurately records his field observations to accumulate data for the solution of a problem.*

geology \jē-'äl-ə-jē\ *n.*
EARTH SCIENCE. The science that includes the study of the origin, history, structure and chemical and physical nature of the earth.

Plant and animal fossils are studied in GEOLOGY *to learn more about the history of a given area.*



GEOMAGNETISM

geomagnetism \ˌjē-(ˌ)ō-'mag-nə-ˌtiz-əm\ *n.*
EARTH SCIENCE. The magnetic force in the magnetic field of the earth.

GEOMAGNETISM *causes a compass needle to indicate the direction of the magnetic pole.*

geometric progression \ˌjē-ə-'met-rik prə-'gresh-ən\
MATHEMATICS. An ordered set of numbers, any one of which,

after the first, is determined by multiplying the preceding one by a given number, or ratio.

The sequence 72, 48, 32, and 21⅓ is a GEOMETRIC PROGRESSION *in which the common ratio is ⅔.*

41.6
10.4
2.6
.65
.1625

(COMMON RATIO = ¼)

GEOMETRIC PROGRESSION

geometry \jē-ˈäm-ə-trē\ *n.*

MATHEMATICS. That division of the science of mathematics dealing with the study of the properties of, and the relationships between, sets of points, lines and other figures in a space that conform to a preassigned set of consistent principles or postulates.

Utilizing the principles of GEOMETRY, *one can determine distances that he cannot measure directly.*

geomorphology \ˌjē-ə-(ˌ)mȯr-ˈfäl-ə-jē\ *n.*

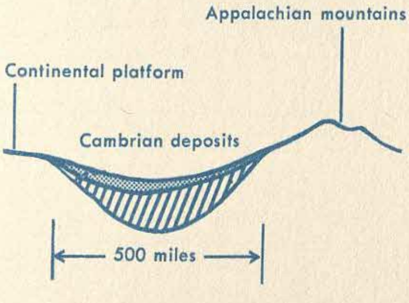
EARTH SCIENCE. The branch of geology concerned with the physical features of the earth, their form, nature, origin, development and the changes they are undergoing; the science of land forms.

GEOMORPHOLOGY *includes the study of the effects produced on the earth's surface by glaciers, streams, landslides, faults and volcanoes.*

geophysics \ˌjē-ə-ˈfiz-iks\ *n.*

PHYSICS and EARTH SCIENCE. The branch of earth science concerned with the motion, constitution and structure of the earth and its atmosphere, with deformations in, and movements of, the earth's crust and with other physical properties, such as climate changes and the electric and magnetic fields of the earth.

Determining the internal structure of the earth is a problem of GEOPHYSICS.



GEOSYNCLINE

geoscience \ˌjē-ō-ˈsī-ən(t)s\ *n.*

EARTH SCIENCE. Any of the sciences dealing primarily with the earth, its form, history, motion and other characteristics.

Geology is the most general GEOSCIENCE.

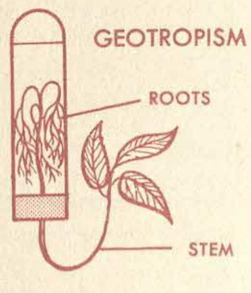
geosyncline \ˌjē-ō-ˈsin-ˌklīn\ *n.*

EARTH SCIENCE. A downward fold or warp in the earth's crust that involves an area of several hundred square miles; a very large syncline.

A GEOSYNCLINE *characteristically has great thicknesses of sediment that have accumulated over a long period of time.*

geotaxis \ˌjē-ō-ˈtak-səs\ *n.*
BIOLOGY. The movement of an organism resulting from its response to the force of gravity.

A GEOTAXIS *is equivalent to a geotropism, except that the former is usually applied to a change in place or location, while the latter generally deals with a change in relative position or direction.*

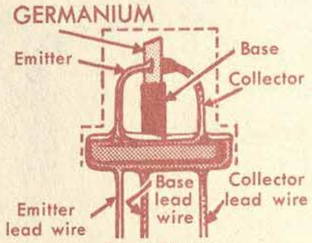


geotropism \jē-ˈä-trə-ˌpiz-əm\ *n.*
BOTANY. Any response of a growing plant to the force of gravity, exhibited by the curvature of some plant parts or by the downward growth of roots.

The root of a bean seed growing downward, regardless of the position of the seed, is an example of GEOTROPISM.

geriatrics \ˌjer-ē-ˈa-triks\ *n.*
MEDICINE. The branch of medical science specifically concerned with problems of nutrition, hygiene and diseases of old age.

Since the average life-span of people has increased over the past few years, GERIATRICS *has become an important medical specialty.*



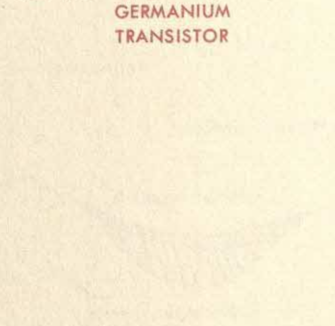
GERMANIUM TRANSISTOR

germ \ˈjərm\ *n.*
BIOLOGY and MEDICINE. Any microorganism, but especially any of the disease-causing bacteria; also, any small, developing combination of cells, such as a fertilized egg, a seed or a bud.

The term microorganism is preferred in science to the use of the word GERM.

germanium \(ˌ)jər-ˈmā-nē-əm\ *n.*
CHEMISTRY. A brittle, silver-white metallic element resembling silicon. It is comparatively rare and usually is found mixed with other metallic ores. Symbol, Ge; atomic number, 32; atomic weight, 72.59.

GERMANIUM *is used in producing transistors for radios and other electrical devices.*

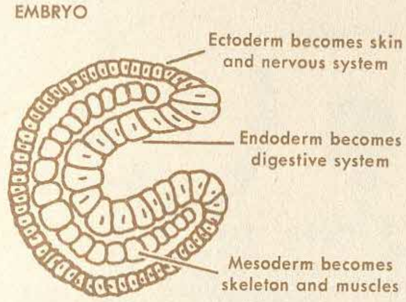


GERM CELL

germ cell \ˈjərm ˈsel\
An older term for gamete. See *gamete.*

germicide \ˈjər-mə-ˌsīd\ *n.*
MEDICINE. Any agent that destroys microorganisms (germs), especially disease-producing varieties.

Isopropyl alcohol is often used to sterilize medical instruments because it is a good GERMICIDE.


EMBRYO
Ectoderm becomes skin and nervous system
Endoderm becomes digestive system
Mesoderm becomes skeleton and muscles

GERM LAYER

germinate \'jər-mə-ˌnāt\ *v.*

BIOLOGY. To begin to grow and develop from seeds and spores.

Seeds do not GERMINATE *until conditions of sufficient moisture and temperature are maintained.*

germ layer \'jərm 'lā-ər\

ANATOMY and ZOOLOGY. Any of the three layers of cells formed in an egg shortly after fertilization.

A number of specific tissues and organs develop from each GERM LAYER.

germ plasm \'jərm 'plaz-əm\

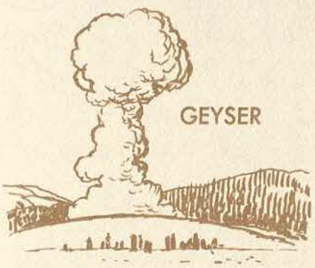
BIOLOGY. The portion of the protoplasm in gametes containing the genes and chromosomes that determine hereditary characteristics.

GERM PLASM *is transmitted to offspring through the reproductive cells.*

germ theory \'jərm 'thē-ə-rē\

BIOLOGY. The theory of biogenesis stating that each living organism has its origin in some other living organism and cannot be produced from nonliving matter.

Acceptance of the GERM THEORY *and rejection of the theory of spontaneous generation led to the conquest of many communicable diseases.*



GEYSER

gestation \je-'stā-shən\

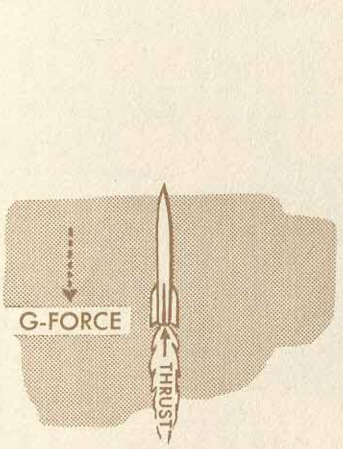
PHYSIOLOGY and ZOOLOGY. The period of time from conception to birth during which the young of mammals are carried in the uterus of the mother.

The period of GESTATION *for human beings is 9 months, but for elephants it is 22 months.*

geyser \'gī-zər\ *n.*

EARTH SCIENCE. A very hot spring that erupts periodically and ejects hot water, steam and sometimes mud.

Old Faithful is the most famous GEYSER *in the United States.*



g-force \'jē-ˌfō(ə)rs\ *n.*

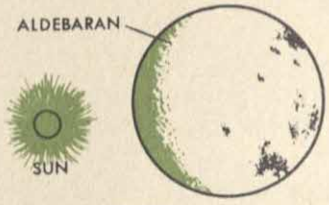
ASTRONAUTICS. The force exerted on an object by gravity or by reaction to acceleration or deceleration.

An astronaut at blast-off is subject to many times the normal G-FORCE.

giant star \'jī-ənt 'stär\

ASTRONOMY. A star whose diameter is much greater than that of most other stars of comparable surface temperature.

Aldebaran is a GIANT STAR *having a mass 4 times, and a diameter 60 times, that of our sun.*



GIANT STAR

gibbous \'jib-əs\ *adj.*

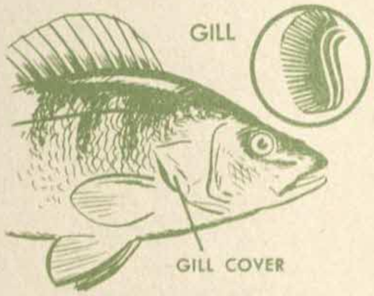
ASTRONOMY. Referring to the moon or a planet when more than half but not all of the object appears to be illuminated.

The GIBBOUS *moon, between the first-quarter moon and full moon, appears in the eastern half of the sky at sunset.*

gill \'gil\ *n.*

ZOOLOGY. The respiratory organ of certain aquatic animals. Blood in the gills absorbs oxygen from water.

A GILL *in fish performs the same function as a lung in human beings.*



gill slits \'gil 'slits\

ZOOLOGY. Openings on the sides of the pharynx of some aquatic animals through which water is forced out from the throat.

GILL SLITS *appear in early stages of the human embryo, although they disappear long before birth.*

girdle \'gərd-ᵊl\ *n.*

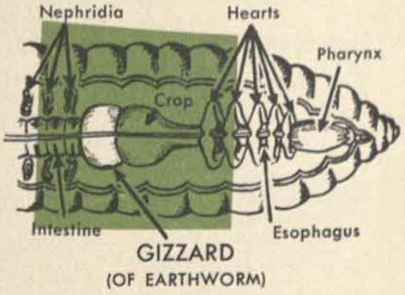
1. ANATOMY and ZOOLOGY. The bony sections of the internal skeleton of vertebrates to which legs and arms are attached. 2. BOTANY. A ring cut around the trunk of a tree so as to remove all tissues outside the xylem.

The legs of man are attached to the pelvic GIRDLE, *and arms to the pectoral girdle.*

gizzard \'giz-ərd\ *n.*

ZOOLOGY. A muscular grinding chamber in the digestive system of many birds and other animals; a second stomach.

An earthworm as well as a grasshopper has a GIZZARD.



GIZZARD
(OF EARTHWORM)

glacial drift \'glā-shəl 'drift\

EARTH SCIENCE. Rocks and earth left by the movement and melting of a glacier; a glacial deposit.

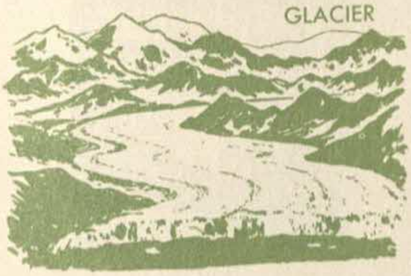
GLACIAL DRIFT *may have been carried for great distances before being deposited.*

glacial grooves \'glā-shəl 'grüvz\
EARTH SCIENCE. Large furrows left by moving glaciers as the ice-rock mixture wears away the land.

GLACIAL GROOVES *provide evidence for determining the direction of glacial movement.*

glaciation \ˌglā-s(h)ē-'ā-shən\ *n.*
EARTH SCIENCE. The changing of the earth's face through erosion and deposition by glacial ice.

The Great Lakes are a result of GLACIATION.

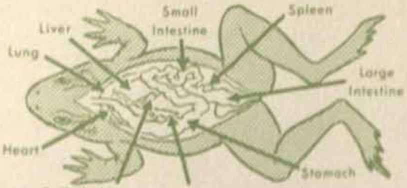

GLACIER

glacier \'glā-shər\ *n.*
EARTH SCIENCE. A huge mass of moving ice occurring in two forms: In the mountainous glacier, called by some an ice river, the mass moves in a definite direction, having a clearly-defined, though variable, width. In the continental glacier, or ice sheet, the mass spreads out from a center point in more than one direction.

Icebergs occur when a GLACIER *reaches the sea and large chunks of it break off and float away.*

gland \'gland\ *n.*
ANATOMY and ZOOLOGY. An organ that produces a specific secretion or product, such as adrenalin from the adrenals or perspiration from a sweat gland.

A digestive GLAND *secretes its product through a duct, while endocrine gland secretions go directly into the bloodstream.*



GLAND
(PANCREAS)

glass \'glas\ *n.*
CHEMISTRY and EARTH SCIENCE. A rigid, brittle, often transparent substance, the basic ingredient of which is generally silica, SiO_2, or sand. Common glass is produced by adding sodium carbonate and carbon to the silica, melting the mixture and rapidly cooling the liquid to harden it without crystallization. Obsidian is a naturally-occurring glass.

The physical properties of GLASS, *such as hardness, melting point and index of refraction, are varied by the kinds and proportions of the ingredients used in producing it.*

glaze \'glāz\
1. CHEMISTRY (N.). The vitreous, or glassy, surface on pottery, tile, brick and other ceramic objects, produced by fusing such substances as sodium silicate and aluminum silicate with the molten material. (V.). To produce the appearance described above. 2. EARTH SCIENCE (N.). Smooth, transparent ice.

A colored GLAZE *can be produced by adding certain substances to the molten mass.*

glide \'glīd\ *v.*

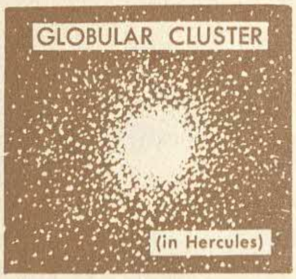
AERONAUTICS. To descend in a heavier-than-air craft with little or no engine thrust.

Sailplanes are able to GLIDE *at a shallower angle than powered aircraft.*

glider \'glīd-ər\ *n.*

AERONAUTICS. A fixed-wing aircraft designed for gliding and, ordinarily, having no engine.

A GLIDER *is often towed by an airplane to a location relatively close to the landing site.*



globular cluster \'gläb-yə-lər 'kləs-tər\

ASTRONOMY. A dense, spherical-shaped mass of thousands of stars. Most are visible only with the aid of a telescope.

One well-known GLOBULAR CLUSTER *appears in the constellation Hercules.*

globule \'gläb-(ˌ)yü(ə)l\ *n.*

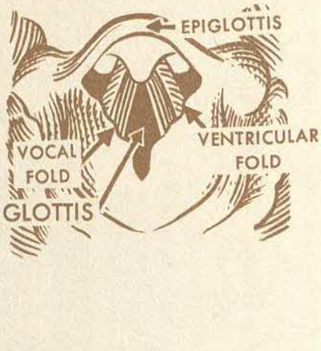
1. CHEMISTRY. A small, spherical particle. 2. MEDICINE. A pellet of medicine. 3. PHYSIOLOGY. A blood corpuscle or disk.

A butter-fat GLOBULE *in milk is microscopic in size.*

globulin \'gläb-yə-lən\ *n.*

BIOLOGY and MEDICINE. A class of protein compounds found in plants and animals, characteristically insoluble in water but soluble in saline solutions; also, serum globulin.

Probably the best-known GLOBULIN *is gamma globulin, used in threatened epidemics, as of infectious hepatitis.*



glottis \'glät-əs\ *n.*

ANATOMY. The vocal mechanism in the larynx, including the vocal cords and the opening between them.

The GLOTTIS *is located at the entrance to the windpipe.*

glucose \'glü-ˌkōs\ *n.*

BIOLOGY and CHEMISTRY. $C_6H_{12}O_6$. A simple sugar produced by photosynthesis and found in fruit, in honey and in the body fluids of animals.

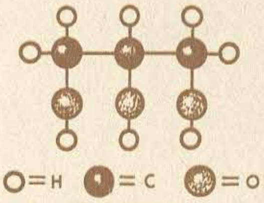
GLUCOSE *is sometimes used in intravenous feeding.*

gluten \'glüt-ᵊn\ *n.*

BIOLOGY. A sticky, nonstarch substance in wheat and other grain flours. It is protein in composition.

A flour having a high percentage of GLUTEN *is used in making a special gluten bread.*

glycerin \'glis-(ə-)rən\ *n.*
Another name for glycerol. See *glycerol.*



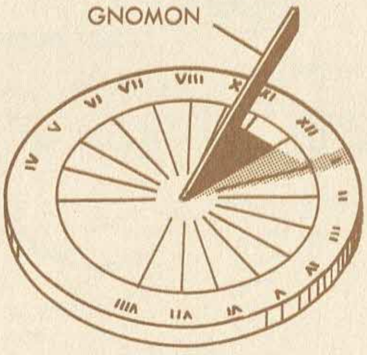
GLYCEROL
(Molecular structure)

glycerol \'glis-ə-ˌrȯl\ *n.*
CHEMISTRY and MEDICINE. $C_3H_5(OH)_3$. A colorless, odorless, sweet-tasting compound whose boiling point is 290°C. It has many medical uses, such as an application for inflammations, and is used industrially in the production of plastics and dynamite; also called glycerin.

GLYCEROL *is a by-product of soap manufacturing.*

glycogen \'glī-kə-jən\ *n.*
PHYSIOLOGY and ZOOLOGY. $(C_6H_{10}O_5)x$. A complex polysaccharide that is the common form of carbohydrate storage material in animals.

GLYCOGEN, *sometimes called animal starch, is stored chiefly in the liver and muscles of animals.*



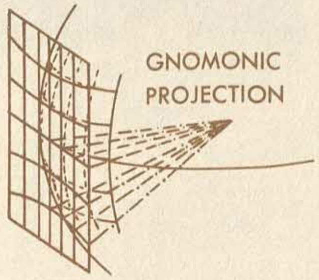
SUNDIAL

gneiss \'nīs\ *n.*
EARTH SCIENCE. A metamorphic rock composed of alternating bands of granular minerals and flat, sheetlike minerals.

Some GNEISS, *such as biotite gneiss or granite gneiss, is named according to the predominant minerals or parent rock from which it was formed.*

gnomon \'nō-ˌmän\ *n.*
1. ASTRONOMY. A column or rod set perpendicular to the earth for purposes of telling time and latitude by the shadow it casts. 2. MATHEMATICS. The portion of surface lying between two unequal but similar parallelograms that have one pair of equal angles coinciding; also, the remainder of a parallelogram after one corner has been removed.

The pointer on a sundial is a GNOMON.



gnomonic projection \nō-'män-ik prə-'jek-shən\
EARTH SCIENCE. The projection of a portion of the earth's curved surface onto an imaginary flat surface tangent to it; also, a type of map projection.

Even though a GNOMONIC PROJECTION *distorts the earth's surface, it is useful in navigation because a great circle on the globe becomes a straight line on the map.*

gold \'gōld\ *n.*
CHEMISTRY and EARTH SCIENCE. A very dense, metallic element, yellow, soft and readily shaped, found in the uncombined state

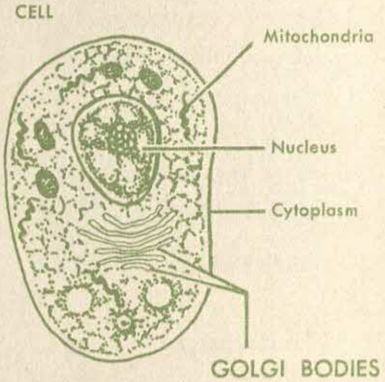
in very limited quantity, chiefly in certain sands and quartz veins. Symbol, Au; atomic number, 79; atomic weight, 197.2.

GOLD is present in seawater, but the cost of recovering it is greater than the value of the gold obtained.

Golgi apparatus \'gȯl-(ˌ)jē ˌap-ə-'rat-əs\

BIOLOGY. Golgi bodies appearing in a netlike pattern or some other arrangement, rather than as disconnected particles.

The GOLGI APPARATUS is named for Camillo Golgi, an Italian physician who first saw these structures in 1898.



Golgi bodies \'gȯl-(ˌ)jē 'bäd-ez\

BIOLOGY. Structures resembling bundles of parallel, very small membranes visible in the cytoplasm of some cells when special stains are used. They occur near the nucleus and are most numerous in the cells that make up glands.

The exact function of GOLGI BODIES is unknown, but scientists think it is possible that they are involved in the secretion of cell products.

gonad \'gō-ˌnad\ *n.*

ANATOMY and ZOOLOGY. A gland in animals that produces sexual reproductive cells, or gametes.

The GONAD of a female is called an ovary.

goniometer \ˌgō-nē-'äm-ət-ər\ *n.*

1. PHYSICS. An instrument used to measure an angle, such as that between two surfaces of a crystal, by the reflection of light rays from both surfaces. 2. ENGINEERING. An instrument using fixed and movable coils in radio circuits to replace the movable antenna in a radio range system.

A GONIOMETER is useful to the mineralogist in the study of a crystal.

gorge \'gȯ(ə)rj\ *n.*

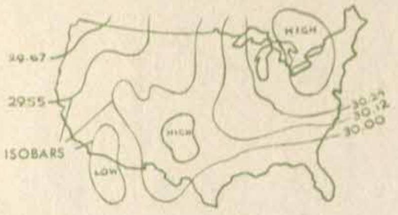
EARTH SCIENCE. A narrow passage with steep, rocky sides; also, the narrowest part of a pass; also called canyon, ravine or gulch.

A river or stream usually forms the GORGE through which it flows.

gox \'gäks\ *n.*

ASTRONAUTICS. A term used in rocketry to designate oxygen in its gaseous, rather than its liquid, form.

GOX is usually used in association with lox, or liquid oxygen.



GRADIENT

gradation \grā-'dā-shən\ *n.*

1. EARTH SCIENCE. The process of bringing a surface to grade through erosion, transportation and deposition. 2. A successive arrangement by increase or decrease in grade, class, degree or size.

GRADATION *of land by streams and rivers produces a plain.*

grade \'grād\ *n.*

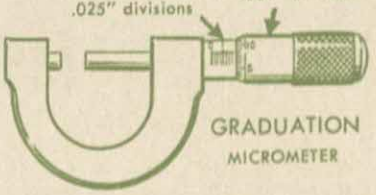
EARTH SCIENCE. The slope of an area or path, particularly of a stream bed whose slant is such that the stream neither erodes nor deposits; also, any measure of inclination, usually expressed in percent.

One of the principles of modern highway construction is the avoidance of a steep GRADE.

gradient \'grād-ē-ənt\ *n.*

The amount of change of a quantity, such as temperature or air pressure, at fixed intervals along a line; also, the slope of a line or surface measured from a horizontal line; also, the rate of change of anything, in size or in any measurable quantity.

The air pressure GRADIENT *around a low or high pressure center is shown on weather maps by the spacing between isobars.*



GRADUATION

MICROMETER

gradual metamorphosis \'graj-(ə-)wəl ,met-ə-'mȯr-fə-səs\

ZOOLOGY. A type of development among insects in which the young resemble the adult in general form and habit. The wingless and sexually-immature young are called nymphs.

In GRADUAL METAMORPHOSIS, *a grasshopper passes through many nymphal stages.*

graduation \,graj-ə-'wā-shən\ *n.*

MATHEMATICS. The changing from one level, amount, quality or size to another by regular stages; also, the markings on a scale indicating these changes.

The GRADUATION *on an inexpensive thermometer may be inaccurate.*

grafting \'graft-iŋ\ *n.*

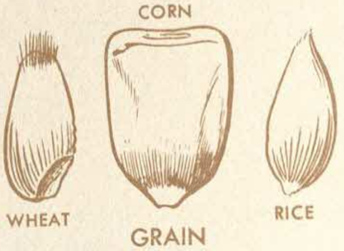
1. BOTANY. The process of placing a part of one plant into another plant in such a position that it unites and continues to grow. 2. MEDICINE. The process of transplanting skin or other tissues.

GRAFTING *is successful only with plants of the same kind or closely-related varieties.*

Graham's law \'grā-əmz 'lȯ\

CHEMISTRY and PHYSICS. A law relating the rates at which different gases diffuse. The law states that the rates of diffusion of two gases are inversely proportional to the square roots of their densities: $\frac{r_1}{r_2} = \frac{\sqrt{d_2}}{\sqrt{d_1}}$, in which r_1 and d_1 equal the rate of diffusion and the density of one gas, and r_2 and d_2 equal the rate of diffusion and density of a second gas.

The densities of gases used in calculations involving GRAHAM'S LAW *are determined at standard temperature and pressure.*



GRAIN

grain \\'grān\\ *n.*
1. BOTANY. The seed or fruit of certain cereal plants, such as wheat, corn and rice. 2. EARTH SCIENCE. The individual crystals or particles of rock occurring either loose or bound with others in a solid rock mass; also, the direction in which some rocks, especially granite, will split easily. 3. ASTRONAUTICS. A rod-shaped mass of solid propellant for a rocket. 4. MATHEMATICS. The smallest weight unit in the metric system, equal to 0.0648 gram.

GRAIN *is one of the most widely-known foods, since it is used in man's own diet and in feeding livestock.*

kilogram = 1,000 grams = 35.27 ozs.
hectogram = 100 grams = 3.5274 ozs.
decagram = 10 grams = 0.3527 oz.

GRAM = 0.03528 oz.

decigram = 0.1 gram = 0.00353 ozs.
centigram = 0.01 gram = 0.00035 ozs.
milligram = 0.001 gram = 0.00004 ozs.

gram \\'gram\\ *n.*
CHEMISTRY and MATHEMATICS. A unit of mass of the metric system. As weight, a gram is equal to 0.03528 ounce.

The milligram is 1/1,000 the weight of a GRAM.

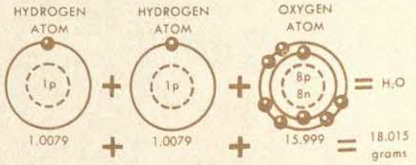
gram atom \\'gram 'at-əm\\
CHEMISTRY. The amount in grams of an element equal to its atomic weight.

In the revised scale of atomic weight values in which carbon 12 is the standard, a GRAM ATOM *of oxygen is 15.999 grams.*

gram-atomic weight \\'gram ə-'täm-ik 'wāt\\
Another term for gram atom. See *gram atom.*

gram-formula weight \\'gram 'fȯr-myə-lə 'wāt\\
CHEMISTRY. The sum of the gram-atomic weights of all the atoms in the formula of a compound, applied to both covalent and ionic compounds; a mole.

The GRAM-FORMULA WEIGHT *of water is slightly more than 18 grams.*



GRAM-FORMULA WEIGHT

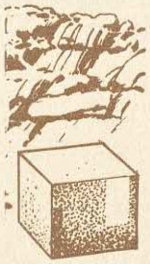
gram mole \\'gram 'mōl\\
Another term for gram-molecular weight. See *gram-molecular weight.*

gram-molecular volume \'gram mə-'lek-yə-lər 'väl-yəm\
CHEMISTRY. The volume occupied by one gram-molecular or gram-formula weight of a gaseous substance. It is 22.4 liters when the temperature is 0° C. and the pressure is 760 mm. of mercury.

The GRAM-MOLECULAR VOLUME *of a gas can be used to determine the molecular weight of that gas.*

gram-molecular weight \'gram mə-'lek-yə-lər 'wāt\
CHEMISTRY. The amount in grams of a compound equal to its molecular weight.

The term GRAM-MOLECULAR WEIGHT, *or gram molecule, can be used only for covalent compounds because ionic compounds do not form molecules.*



GRANITE

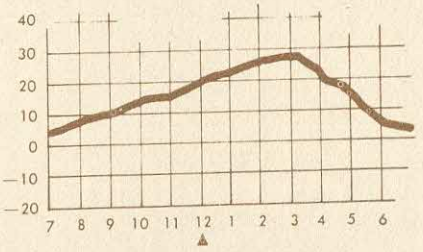
gram molecule \'gram 'mäl-i-ˌk(y)ü(ə)l\
CHEMISTRY. Another term for gram-molecular weight. See *gram-molecular weight.*

granite \'gran-ət\ *n.*
EARTH SCIENCE. A fine- to coarse-grained, very hard igneous rock consisting of quartz, feldspar and small amounts of other minerals.

The color of GRANITE *comes mainly from the feldspar it contains and may range from light gray through pink or red.*

granules \'gran-(ˌ)yü(ə)lz\ *n.*
1. ASTRONOMY. Areas on the surface of the sun that give it a mottled appearance and are formed by gases coming from below the surface. 2. BIOLOGY. Small particles in cell bodies, generally assumed to be a source of stored food in the cell.

GRANULES *on the sun can be seen only with the aid of a telescope equipped with special filters.*



GRAPH

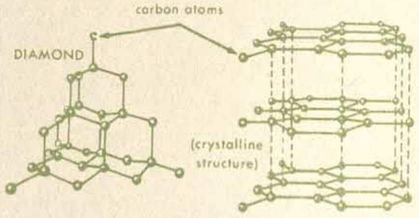
graph \'graf\ *n.*
MATHEMATICS. A diagram or figure that represents a relation between numbers; also, a record of such relations produced by a mechanism, such as a thermograph, that records temperatures over a period of time.

A GRAPH *drawn by a seismograph records the severity, frequency and duration of earthquakes.*

graphics \'graf-iks\ *n.*
The art of drawing, using principles of perspective and projection and involving geometric and trigonometric calculations, by means of which certain engineering and architectural informa-

tion, such as the design of, and stress upon, structure, is obtained.

The preparation of one who plans to become an architectural engineer requires a careful study of GRAPHICS.



GRAPHITE

graphite \'graf-ˌīt\ *n.*
EARTH SCIENCE. A black, greasy-feeling, soft mineral, pure carbon, in one of its two naturally-occurring free states, the other state being the diamond.

GRAPHITE *is a major ingredient of pencil leads.*

grass \'gras\ *n.*
BOTANY. Generally, any green plant with long, narrow, bayonet-shaped leaves; specifically, the plants of the family Poaceae that have jointed stems, flowers borne on projections called spikelets and fruit resembling seeds.

Wheat is a true GRASS.

GRAVEL

gravel \'grav-əl\ *n.*
EARTH SCIENCE. A deposit of rounded stones larger than two mm. in diameter that are usually intermixed with smaller particles of sand or clay; also, stones that are rounded and deposited by the action of moving water.

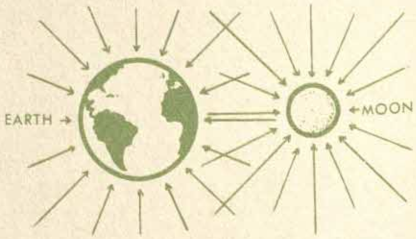
GRAVEL *is used in road construction as a roadbed material and as an aggregate in concrete.*

gravimetric \ˌgrav-ə-'met-rik\ *adj.*
CHEMISTRY and PHYSICS. Referring to measurement by weight.

By means of GRAVIMETRIC *analysis, the amount of each element in a compound or of each component of a mixture can be determined.*

gravitation \ˌgrav-ə-'tā-shən\ *n.*
PHYSICS. The attraction of all particles and masses in the universe by all other masses and particles.

The law of GRAVITATION *states that the attraction between any two objects is proportional to the product of their masses and to the inverse square of the distance between them.*



GRAVITATIONAL FIELD

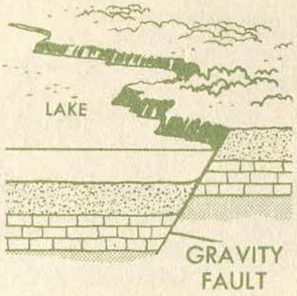
gravitational field \ˌgrav-ə-'tā-shnəl 'fēld\
PHYSICS. A region in which an object or mass is subjected to a gravitational force.

The force of the GRAVITATIONAL FIELD *of the moon, along with other forces, including the gravitational force of the sun, produces tides in oceans and lakes.*

gravity \'grav-ət-ē\ *n.*

PHYSICS. The force that attracts all bodies toward the center of the earth. Gravity refers specifically to the gravitational effect of the earth.

The force of GRAVITY *causes objects to accelerate toward the earth at about 32.12 feet per second*



gravity fault \'grav-ət-ē 'fölt\

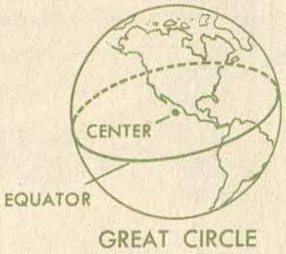
EARTH SCIENCE. A fracture of the earth's surface in which a large mass of earth sinks down at the line of fracture; also, a fault in which the hanging wall has moved down with reference to the footwall.

The lowering of a section of the earth resulting from a GRAVITY FAULT *can cause a lake to form in the depression.*

gray matter \'grā 'mat-ər\

ANATOMY. The nerve tissue of the brain and spinal cord that is made up chiefly of nerve cell bodies, as contrasted with white matter that consists mainly of nerve fibers.

GRAY MATTER *is found in the central portion of the spinal cord.*



great circle \'grāt 'sər-kəl\

MATHEMATICS. A circle on a sphere resulting from the intersection of the sphere and a plane passing through the center of the sphere.

If we consider the earth a sphere, then the equator is a GREAT CIRCLE, *as are all meridians.*

greenhouse effect \'grēn-ˌhaüs i-'fekt\

PHYSICS. The heating of any enclosed space by the sun's rays shining on, or through, its surface, thus raising the temperature above that of the air outside the enclosure; also, the heating of the earth caused by the fact that the relatively-short wavelengths of solar radiation penetrate the atmosphere readily and warm the earth by absorption, but the upward radiation by the earth has relatively-long wavelengths that do not so readily penetrate the atmosphere.

The heating of the interior of an automobile with its windows closed is an example of the GREENHOUSE EFFECT.

Greenwich time \'grin-ij 'tīm\

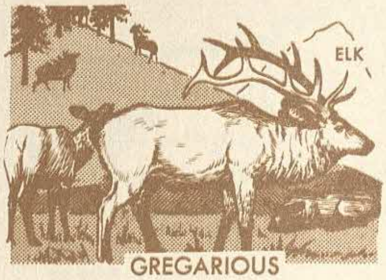
The time that is used as a reference for time all over the world; Greenwich mean time. The longitude that passes through Greenwich, England, is the prime meridian, and midnight there is the starting time for the world's day.

GREENWICH TIME *is now synonymous with universal time.*

gregarious \gri-'gar-ē-əs\ *adj.*

1. ZOOLOGY. Living in the company of others of the same species, as in flocks. 2. BOTANY. Growing in groups or clusters.

Because elks live in herds, they are called GREGARIOUS *animals.*



GREGARIOUS

Gregorian calendar \gri-'gōr-ē-ən 'kal-ən-dər\

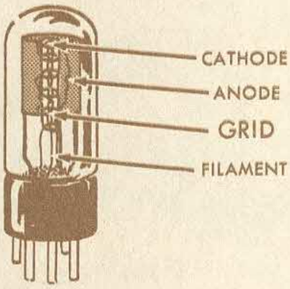
MATHEMATICS. The calendar in use today, accurate within 26 seconds per year, as distinguished from the Julian calendar, used before 1582, that had an error of over 11 minutes per year.

England did not adopt the GREGORIAN CALENDAR *until 1752 and Russia not until 1918.*

grid \'grid\ *n.*

ENGINEERING. A control electrode in an electron tube, consisting generally of parallel wires or open mesh placed in the path of electrons flowing from the cathode to the anode and activated by voltages from an external source.

A small change in the voltage on the GRID *in an electron tube produces a large change in the flow of electrons from the cathode to the anode.*



grotto \'grät-(ˌ)ō\ *n.*

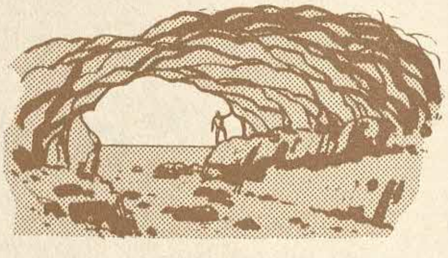
EARTH SCIENCE. A cavernlike recess; a small cave.

A GROTTO *is formed either by seepage or by lateral stream erosion.*

ground \'grau̇nd\

1. EARTH SCIENCE (N.). Material of the surface of the earth; soil; also, a particular region or area of land. 2. PHYSICS (N.). An electrical conductor connected to the earth, often by means of a metallic plate, rod or similar device buried there; also, a large common conductor, the potential of which is zero, such as the metallic frame of an automobile. 3. ENGINEERING (V.). To connect a part of a circuit to a ground.

Arctic GROUND, *called permafrost, stays frozen all year to a depth of a few inches below the surface.*



GROTTO

ground-controlled approach \'grau̇nd kən-'trōld ə-'prōch\

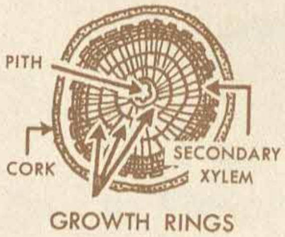
AERONAUTICS. A landing approach in which the pilot is continuously advised from the ground by radio of his position and direction as determined by radar; *abbr.* GCA.

A GROUND-CONTROLLED APPROACH *is necessary under conditions of poor visibility.*

ground water \'grau̇nd wȯt-ər\

EARTH SCIENCE. The subsurface water that accumulates in the zone of saturation; water below the water table.

GROUND WATER *can be obtained from springs or wells.*



GROWTH RINGS
(3)

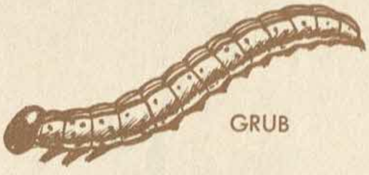
ground wave \'grau̇nd 'wāv\

PHYSICS. A surface wave; that is, a radio wave that travels from the transmitter to the radio receiver in a region along and above the surface of the earth and that is not reflected by the ionosphere.

A GROUND WAVE *is weakened by the earth's absorption of its energy and, as a result, is not reliable for long-distance radio communication.*

group \'grüp\ *n.*

MATHEMATICS. A nonempty set of elements that is closed under one binary operation (to be denoted by the symbol O) and that satisfies the following three properties: (*a*) The associative law holds; i.e., if a, b and c are elements of the set, then $(a\cdot b)\cdot c = a\cdot(b\cdot c)_1$. (*b*) The set contains an identity element, e, such that for every element a in the set, $a\cdot e = e\cdot a = a$. (*c*) For every element a in the set, there exists an element a^1 in the set such that $a\cdot a^1 = a^1\cdot a = e$.



The concept of a GROUP *is due to the work of two young mathematicians, Evariste Galois, a Frenchman, and Niels Henrik Abel, a Norwegian.*

growth rings \'grōth 'riŋz\

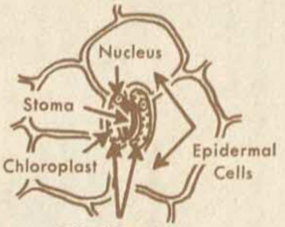
1. BOTANY. Successive layers of large and small xylem cells in a tree trunk or twig; also called annual rings. 2. ZOOLOGY. Rings on the outer edge of fish scales.

GROWTH RINGS *in the cross section of a tree are used to estimate its age.*

grub \'grəb\ *n.*

ZOOLOGY. The larva, or wormlike form, of certain beetles.

A GRUB *is hatched from an egg and changes into an adult insect.*



GUARD CELL

guard cell \'gärd 'sel\

BOTANY. Either of two cells surrounding and controlling the size of a stomate.

The shape of a GUARD CELL, *which changes as its internal pressure varies, determines the size of a stomate.*

guidance system \'gīd-ᵊn(t)s 'sis-təm\

ASTRONAUTICS and ENGINEERING. Any system used to control the destination and path of rockets and missiles, generally electronic-mechanical and controlled either from the ground or by instruments within the rocket itself.

One GUIDANCE SYSTEM *gets its bearings from the positions of the stars.*

guided missile \'gīd-əd 'mis-əl\

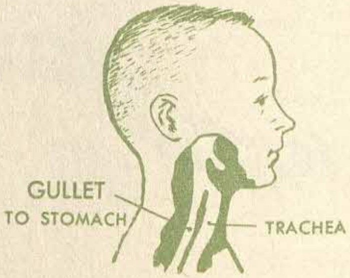
AERONAUTICS and ASTRONAUTICS. An unmanned, self-propelled flying vehicle carrying a destructive load. Its destination and path can be changed after its release, or firing.

One form of GUIDED MISSILE *has a guidance system that enables it to intercept other missiles.*

gulf \'gəlf\ *n.*

EARTH SCIENCE. A large body of water, generally an extension from an ocean or sea, that is surrounded on three sides by land but open to the sea it joins on the fourth; also, an abyss, deep hollow or chasm.

A GULF *is a relatively-large portion of the sea, compared with a bay.*



gullet \'gəl-ət\ *n.*

ANATOMY and ZOOLOGY. The passageway leading from the mouth to the stomach; the esophagus and pharynx.

Muscles of the GULLET *move food down to the stomach by waves of contraction.*

gully \'gəl-ē\ *n.*

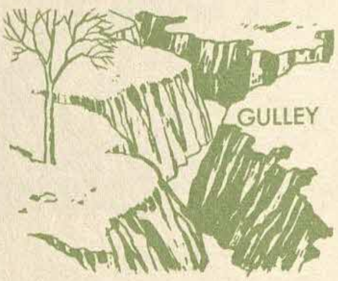
EARTH SCIENCE. A small ravine, hollow or channel in the earth, caused by the eroding action of the runoff from heavy rainfalls.

A GULLY *forms more readily in soil that is not covered with grass or trees.*

gum \'gəm\ *n.*

BOTANY. A sticky substance that oozes from certain trees and other plants and that hardens as it dries. Gum is also sometimes applied to substances other than true gums, such as resins, amber and rubber.

One GUM, *gum arabic, is used in making inks and adhesives.*



gumbo \'gəm-(ˌ)bō\ *n.*

EARTH SCIENCE. A mixture of silty soils that becomes a sticky mud or puttylike clay when wet.

GUMBO *is found most frequently in the southern and western United States, especially in the Mississippi Valley.*

guttation \ˌgə-ˈtā-shən\ *n.*

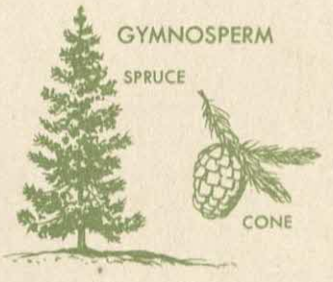
BOTANY. The loss of water by uninjured plants, as contrasted with the loss of water in vapor form (transpiration).

Water from the GUTTATION *of some plants is frequently mistaken for dew.*

gymnosperm \ˈjim-nə-ˌspərm\ *n.*

BOTANY. A plant whose seeds are not enclosed in a seedcase.

The pine or the ginkgo is a GYMNOSPERM.



gynecology \ˌjin-i-ˈkäl-ə-jē\ *n.*

MEDICINE. The branch of medical science concerned with diseases unique to women, particularly of the reproductive and excretory systems.

GYNECOLOGY *is a specialty that arose from obstetrics.*

gypsum \ˈjip-səm\ *n.*

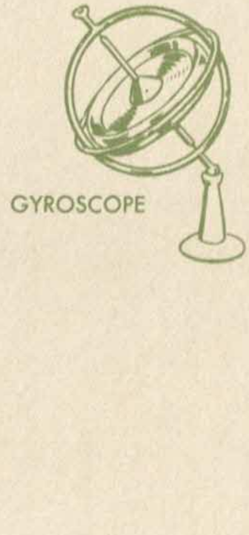
EARTH SCIENCE. $CaSO_4 \cdot 2H_2O$. A soft, colorless mineral that occurs naturally as layered crystals or grains in sedimentary rocks; hydrous calcium sulfate.

GYPSUM *is used in the manufacture of plaster of Paris.*

gyrocompass \ˈjī-rō-ˌkəm-pəs\ *n.*

AERONAUTICS and ASTRONAUTICS. An instrument for navigation that uses an electrically-driven gyroscope as its main component.

A GYROCOMPASS *is standard equipment in all commercial airliners.*



gyroscope \ˈjī-rə-ˌskōp\ *n.*

ENGINEERING and PHYSICS. A device consisting of a wheel or disk fixed to an axle, so supported at its ends that the axis (or axle) can change its direction. Its useful properties include the tendency of the axis, when the wheel is rapidly rotating, to remain pointed in the same direction regardless of changes in position of the mounting. Its wheel and axle tend to change direction at a right angle to the direction of a force applied to the axle at either point of support (precession).

A GYROSCOPE, *as part of a gyrocompass, is useful in navigation because the tendency of the axis to remain in a fixed position when the wheel is rotating will keep it pointed toward true north once it has been set.*

gyrostatics \ˌjī-rə-ˈstat-iks\ *n.*

PHYSICS. The branch of physics concerned with the properties and behavior of rotating bodies.

The principles of GYROSTATICS *explains how a moving bicycle is kept erect by the rider.*